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REMOTE SITE POWER PLANT DESIGN STUDY

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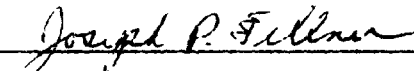
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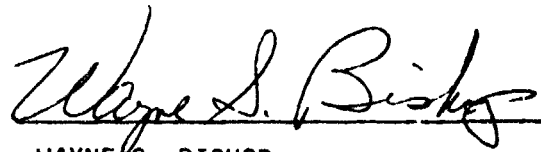
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<p>Two potential applications for a fuel cell power plant, sited/transportable and mobile were evaluated in this study. The major emphasis was centered on the sited/transportable application. The site chosen for analysis was an Air Force radar station in a remote region of Alaska, namely, the Seek Igloo Minimally Attended Radar (MAR) facility at Fort Yukon. The results of this study is that a life cycle cost savings of five (5) million dollars per site would result by the use of fuel cells. The second application studied was a 100kw mobile fuel cell power plant. Result of the sited/transportable power plant design yielded a power plant that was adaptable to the mobile applications.</p>					
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PREFACE

This report describes a study of the application of fuel cell technology to the stationary power requirements of the U.S. Air Force, with particular emphasis on a minimally attended radar installation. The study was conducted for the Air Force Wright Aeronautical Laboratories (AFWAL) by United Technology Corporation (UTC) from September 1982 through September 1984. Mr. Edward Swift was the Program Manager for UTC. Mr. J. Turner and Lt. J. Fellner were the Contract Monitors for AFWAL.

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SUMMARY

INTRODUCTION

The Air Force utilizes transportable electric generators to power tactical loads and support facility equipment in several remote regions where conventional electric power is not available or is not available on a sufficiently reliable basis. Diesel engine generators are currently used for these transportable power requirements but because of the high cost of providing fuel and maintenance services to the remote regions where they are deployed, the Air Force is continually examining alternatives to diesel generators.

Fuel cell power systems which are being developed for commercial use have the potential of being a superior alternative for this Air Force requirement.

At a site typified by a cold region, minimally attended radar installation, \$5,000,000 savings in life cycle costs could result by using fuel cells rather than diesel generators. These savings result because the fuel cell system will require less maintenance, use less fuel than the diesel engine to meet the same requirement and because the fuel cell system can be operated with less manpower. However, it is critical that the Air Force requirements and the on-going DOE/GRI sponsored commercial development program at United Technologies be closely linked if these benefits are to be realized. A unique development program solely to meet the Air Force needs would have an unfavorable cost/benefit ratio.

STUDY APPROACH

The effort reported on herein is a comprehensive study of the fuel cell option. Although the Air Force identifies two needs for transportable power - permanently sited and mobile - the study emphasis is on the sited application. The same conclusions would generally apply to the mobile requirement and the equipment would differ only slightly.

The study program was accomplished in two phases. After an initial conceptual design phase, the effort focused on the specific requirements of a Seek Igloo Minimally Attended Radar Site. This implies a remote site power requirement of 375 kW at 120/208 volts and 60 hertz. The outside air temperature could be as low as -60°F, but the equipment building in which the power plant is located will be maintained above 50°F. There are also substantial thermal loads for both space and water heating which could be partially supplied by cogeneration of electric and thermal energy. An important factor in comparing generation options for these remote sites is the delivered price of the diesel fuel which is assumed to be \$2.50/gallon. Each site is now powered by four 250 kW diesel engine generator sets, to have a site availability of 99%.

The guidance provided by the Air Force at the outset of the program clearly indicated that a unique fuel cell power plant development program to meet these needs would require resources greatly in excess of those available to the Air Force for this equipment. Therefore, a premise of the design study has been that the Air Force power plant be a derivative of a commercial power plant. The most appropriate commercial fuel cell development is the on-going DOE/GRI sponsored program at UTC to evolve an on-site power plant for natural gas applications and this is the basis for the preliminary design evolved in this study to meet the Air Force requirement.

A power plant rating has not been selected in the on-site commercial development program. The current focus is on technology development to reduce the manufacturing costs below those exemplified by the current 40 kW field test power plant. It is anticipated that the combined results of the field test and the technology development program will produce a natural gas power plant design in the range of 40 kW to 200 kW. The Air Force requirement can be satisfied using the appropriate number of units in this range. For the purposes of this study, a rating of 100 kW was selected and the site requirements, including the single spare power plant need for 99% availability, are met for a total of five 100 kW power plants.

DEVELOPMENT NEEDS

The Air Force application cannot use the identical equipment developed for the commercial application. Two requirements for military use will necessitate development not contemplated in the commercial program. Foremost of these is the requirement to use diesel fuel and the second is the need to operate the equipment after it has been stored in sub-freezing temperatures. A significant portion of the study effort was directed to these two requirements.

Fuel Processing

The commercial power plant, with natural gas as the input fuel, will utilize low to moderate temperature (1300°F - 1500°F) catalytic steam reforming to produce the hydrogen-rich fuel required by the cell stack. Extensive development of this concept for fuel cell systems has resulted in an efficient, reliable, long life fuel processing system. However, it is not designed for jet fuel and/or diesel fuels because of inhibiting effect on the reforming reaction of the higher sulfur content of these fuels and the increased tendency for carbon formation and accumulation in the reactor bed. These limitations of the current fuel processing system can be overcome by operating at higher temperatures (1700°F - 1800°F) and four different approaches to do so were investigated in this study.

- 1) Thermal Steam Reforming - This system is similar to the concept presently used except the reforming catalyst bed temperature is maintained about 1800°F rather than 1300-1500°F. However, this requires exotic, high temperature-resistant materials for the reformer tube walls and will not result in a cost effective design.
- 2) Adiabatic Reforming - In this system the necessary higher reforming temperature is maintained by burning some fuel within the reformer bed so that heat does not have to be transferred through the walls of the bed which would be of conventional materials and insulated against internal heat loss. However, the combustion of fuel introduces significant quantities of nitrogen which then become a diluent in the product gas and reduces the fuel cell efficiency.
- 3) Hybrid Reformer - This approach processes the fuel in two steps. A moderate temperature steam reforming stage partially cracks the heavy fuel and a second stage of adiabatic reforming completes the conversion to

hydrogen and oxides of carbon. The wall temperatures in the first phase are low enough that exotic materials are not required and the dilution of the product gas is less than in the adiabatic reformer power plant efficiency penalty.

- 4) Cyclic Reformer - This system results in the highest possible efficiency by the use of two catalytic beds. During the 2-3 minute period that hydrogen is being generated in one bed at the high temperature levels required for complete conversion of heavy fuels, the other bed is regenerated. Heat for the reforming process is supplied by the sensible heat stored in the catalyst and ceramic packing within the reactor and the heat for the regeneration cycle is supplied by combustion of fuel cell anode vent gas during the regeneration cycle.

This study concluded that the cyclic reformer is the best of the four alternatives because of the requirement to operate at the highest possible efficiency. The other systems would lead to a power plant with reduced efficiencies.

Each of the fuel processor options, including the cyclic reformer, will require some technology development to verify the performance using diesel fuel and to establish the required reliability level. Based on extensive analytical work and experimental confirmation at a subscale level, it is concluded that development of the cyclic reformer is reasonable.

Adaptation to Arctic Environment

In addition to the fuel specification, the other developmental need beyond the commercial power plant program, is to provide the capability of storing the fuel cell system for extensive periods at sub-freezing temperatures. The commercial unit will not be stored in a low temperature environment without an external heat source to keep the system above 35°F. Consequently the commercial unit can effectively use a two phase water cell stack cooling system without concern that the water will freeze during shutdown periods and cause component damage. An alternate cooling system is required to meet the Air Force environmental specification. Based on United's experience with air and various liquid coolants, a liquid dielectric fluorocarbon coolant is recommended for this application. This is consistent with United's basic fuel cell design approach to use the higher effectiveness of liquid coolants to maximize power plant efficiency. Liquid cooling is particularly significant for the

Air Force application in order to achieve a higher degree of power plant compactness to facilitate air transportation of the equipment to remote sites. The resulting power plant conceptual design differs from the natural gas commercial design in only these two fundamental areas:

- 1) Diesel fuel requires high temperature reforming and we recommend a cyclic reformer to accomplish maximum power plant efficiency.
- 2) Dielectric cooling of the cell stack is recommended to meet the low temperature environmental requirements.

POWER PLANT CONFIGURATION

Incorporating the cyclic reformer and dielectric cooling into the fuel cell power plant that is developed for on-site commercial applications will provide the Air Force with a remote site 100 kW fuel cell power plant to provide 120/208 volt 60 Hertz power that meets or exceeds power quality requirements of conventional utility sources. The efficiency at rated load will be 41% (6.5 gallons/hour of diesel fuel) and approximately 400,000 Btu/hr will be available as useful heat at a temperature of 150°F. The size (8' x 8' x 11-3/4') and weight (14,500 lbs) will meet the Air Force requirements for air transportability.

The use of fuel cells by the Air Force in such remote sites as the Seek Igloo radar site will result in reducing life cycle energy costs by 24%. This benefit stems from the increased fuel use efficiency, which is especially notable at part power, and the reduced maintenance requirements associated with unattended fuel cell operation.

It is important to reiterate that these operating advantages will accrue only if the fuel cell power plant development and subsequent manufacturing program is closely integrated with the on-going and planned program for on-site commercial applications. A unique Air Force development program and the manufacture of units to meet only the Air Force requirements is not cost effective relative to alternative, more fully developed technologies.

SECTION I APPROACH TO STUDY

APPLICATIONS

Two potential applications for a fuel cell power plant were evaluated in this study. The major emphasis was centered on a military radar station sited in a remote region of Alaska, the SEEK IGLOO Minimally Attended Radar Facility (M.A.R.) as shown in Figure 1. Section 2 presents the results of this design study.

The second application studied was a 100-kW mobile fuel cell power plant. Results of the sited/transportable power plant design yielded a power plant that was adaptable to the mobile applications. Section 5 presents the mobile power plant conceptual design results.

APPROACH

The two applications described above were analyzed and conceptual designs of fuel cell power plants meeting the application requirements were prepared. These conceptual designs were reviewed with the Air Force. The Air Force then selected the sited-transportable fuel cell power plant application for further study, further design work on the mobile application was discontinued.

The preliminary design effort was expanded to include a component evaluation and preliminary hazard analysis to determine deficiencies requiring correction by design analysis, technology improvements and/or refinement thru development.

The sited/transportable power plant design requirements were derived from the SEEK IGLOO facility design data provided by the Alaskan Air Command. The fuel cell power plant installation design approach was to retain much of the facility ancillary equipment now included for the multiple diesel electric generator installation.

With completion of the component evaluation, a Preliminary Hazard analysis and the preliminary design, a logistic fueled power plant development plan was defined. The development plan addresses fuel processor technology requirement and development requisites for winterization and minimizing power plant size. The development plan including task scheduling is submitted as an addendum to this final report.

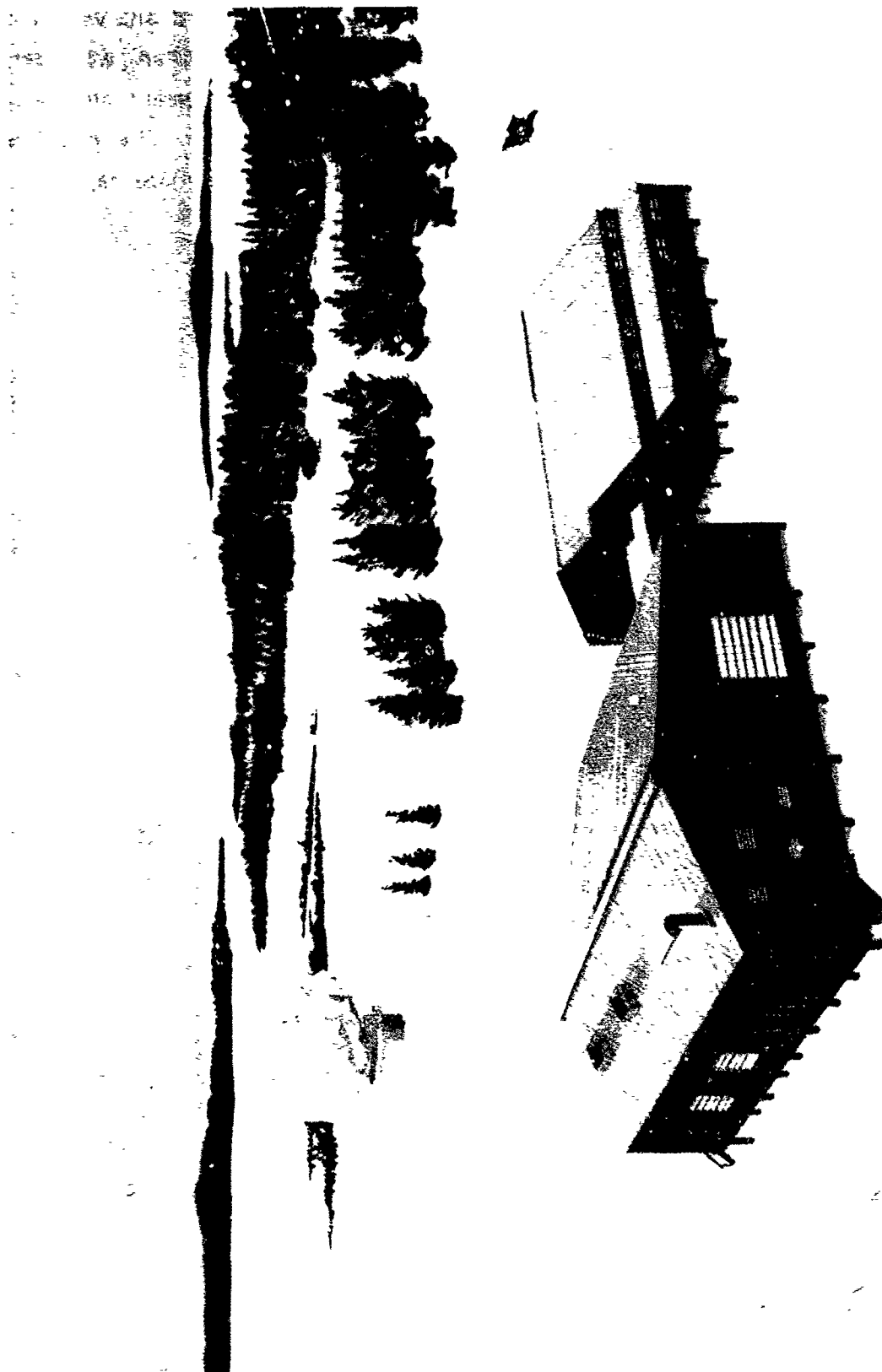


Figure 1. SEEK IGLOO M.A.R. Site

SECTION 2

100-kW REMOTE SITED/TRANSPORTABLE FUEL CELL POWER PLANT DESIGN STUDY

APPLICATION DESCRIPTION

General Application Requirements

The remote nature of the SEEK IGLOO site creates a unique set of application requirements for the fuel cell power plant. For example, the specified fuel type is arctic diesel. This relatively heavy fuel cannot be processed in the high efficiency moderate temperature catalytic steam reformer incorporated in current fuel cell power plants. To process diesel fuel, a higher temperature but yet still efficient fuel processor is required. Power plant efficiency is important since delivered fuel costs are high (~ \$2.50/gal) because of the high transportation cost to the remote site. Another unique characteristic of this site is its extreme climate. The power plant must be designed to withstand non-operating temperatures as low as -60°F when stored at the site. However, the power plant will be operated in an enclosed engine room, where the minimum temperature is no lower than +50°F.

Physical Requirements

The Alaskan Air Command office defined a set of physical requirements for the SEEK IGLOO site. The power plant was designed to conform with the following requirements:

- o Floor area - 2000 ft²
- o Ceiling height - 13 ft
- o Crane capacity - 4000 lbs
- o Water (well) - 120 gpm
- o Floor loading - 100 lbs/ft²
- o Spare parts storage area - 50 ft²

Facility Energy Requirements

Data from the Alaskan Air Command was also used to establish the facility energy requirements. Based on this data, the typical daily load profile in Figure 2 was constructed.

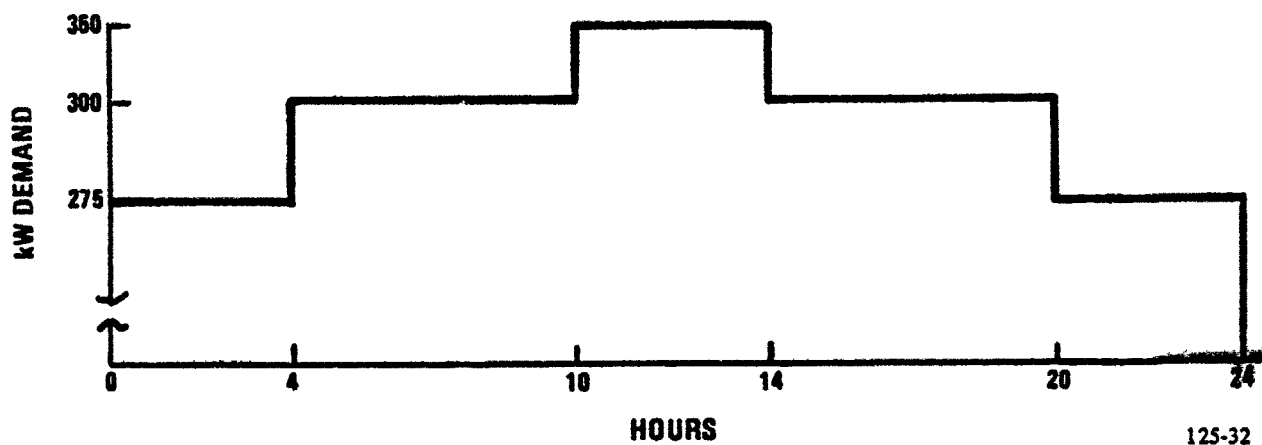


Figure 2. Typical Daily Load Profile

The SEEK IGLOO site also has a substantial thermal energy load. The fuel cell power plants are designed to cogenerate thermal as well as electric power to meet as much of this load as possible. Site thermal interface conditions are as follows:

- o Hot water ~ 45,000-55,000 Btu/hr @ 110°F average
- o Heating ~ 700,000-1,400,000 Btu/hr @ 190°F average

Site electrical interface requirements are 120/208 volts, WYE connection, and 3 phase power @ 60 hertz frequency.

POWER PLANT DESCRIPTION

The remote site power plant was designed to meet the following objectives:

- o Produce 100 kW ac power at rated output.
- o Electrical output to be 3 phase 120/208V 60 Hz.
- o Operate on DFA diesel fuel.
- o Unmanned operation with automatic response to load.
- o High efficiency to minimize amount of fuel transported to remote site.
- o High reliability to minimize maintenance
- o Capability of operation and storage at severe environmental conditions.
- o Weight and size within air transportability limits.

The following Sections describe the conceptual design of a phosphoric acid fuel cell power plant designed to satisfy these objectives.

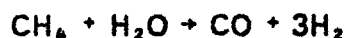
Subsystem Options/Trade-Offs

The program plan specified that the power plant conceptual design should be based on the fuel cell technology being developed by United for on-site commercial and industrial applications. System studies have shown that power plant weight and volume were minimized, and maximum efficiency was achieved with a liquid cooled fuel cell stack for power plants greater than a few kilowatts. The studies also showed that system pressurization was not beneficial for power plants with less than about one megawatt output. These and other on-site power plant studies were reviewed for the Air Force application. It was concluded that it was not necessary or advantageous to change the basic on-site system except for the fuel processor changes to operate on diesel fuel, and to ensure the stack cooling system could accommodate cold weather storage.

Process Description

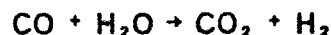
The power plant consists of four major subsystems: the fuel processor, the power section, the power conditioner, and the thermal management subsystems. Functionally these subsystems are the same as the power plants for the gas industry. The relationship between the subsystems are illustrated by the simplified block diagram of the process (Figure 3). The fuel processor gasifies and converts the fuel to a mixture of hydrogen and carbon dioxide. The power section converts the hydrogen to dc power which is then converted to ac power by the power conditioner. The thermal management subsystem cools the power section and provides steam to the fuel processor. Much of the waste heat is recovered and is available for site heating requirements. The energy required by the fuel processor is supplied by burning the residual hydrogen in the anode vent gas from the power section. Steam for processing the fuel is generated by using waste heat to boil water recovered from power section.

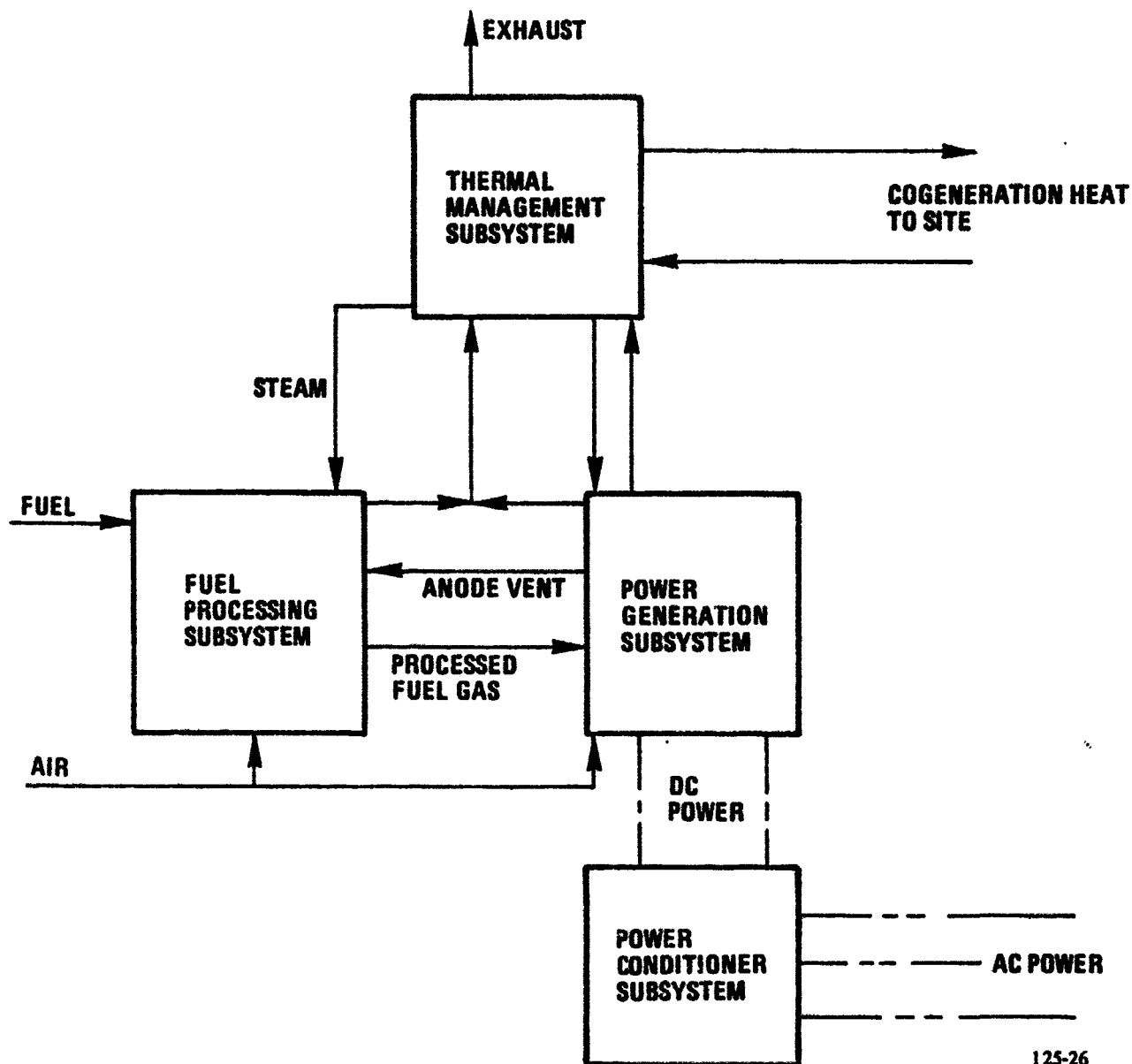
For the on-site power plants operating on natural gas, the fuel processor is a catalytic steam reformer. In this process fuel and steam are mixed. As the mixture flows over a catalyst in tubular reactors, it is converted to hydrogen by the steam reform reaction.



Heat required by this endothermic reaction is provided by the transfer of heat from hot burner gas through the walls of the tubular reactor to the catalysts.

The carbon monoxide is converted to additional hydrogen in a adiabatic reactor by the shift reaction.





125-26

Figure 3. Simplified Block Diagram of Process

Logistically available fuels, such as DFA diesel fuel, are converted to a hydrogen rich gas mixture by similar reactions. However, the reactor must operate at higher temperature to prevent carbon formation and to offset the impact of sulfur in the fuel on catalyst activity. Several modifications of this basic process have been developed for converting diesel fuel to process gas. Trade studies, described in Section IV resulted in this selection of a novel cyclic reformer concept for the conceptual design since it eliminates the materials problems of transferring heat through a metal wall at very high temperatures, and is the most efficient process minimizing fuel consumption. In this process, illustrated in Figure 4, diesel fuel and steam are mixed and converted to process gas in one reactor during half the cycle. Heat for this process is provided by the sensible heat stored in the catalyst and ceramic packing within the reactor. During the second half of the cycle the stored heat is replenished by burning the hydrogen from the anode vent in the reactor. Two reactors are used so one can be making process gas while the other is being regenerated. Process gas is stored in a tank to provide a continuous supply of fuel to the fuel cell during the short transition period. Much of the sulfur in the fuel is absorbed on the catalyst during the make cycle and removed by the burner exhaust gases during the regeneration cycle. The sulfur remaining in the process gas is removed by absorption on a bed of zinc oxide.

The power section uses a stack of series connected phosphoric acid fuel cells to convert the hydrogen in the process gas, plus the oxygen from the process air to dc electrical power and water. The water produced is removed by the cathode exhaust steam. The stack is cooled by a two phase dielectric coolant flowing through coolers in the stack. Two stacks of 158, 1.4 ft² cells electrically connected in series were selected to optimize the power conditioner efficiency with minimum weight and volume. A low profile, two stack, configuration (Figure 5) was selected to satisfy the transportation size requirements.

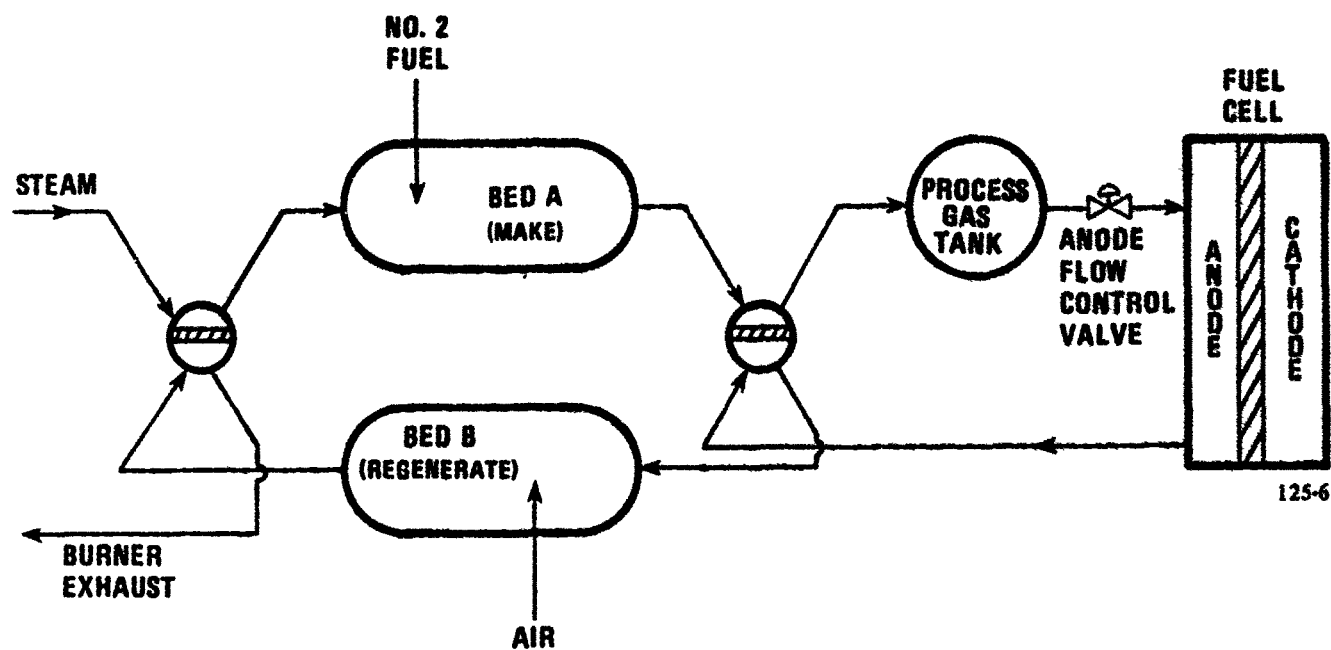
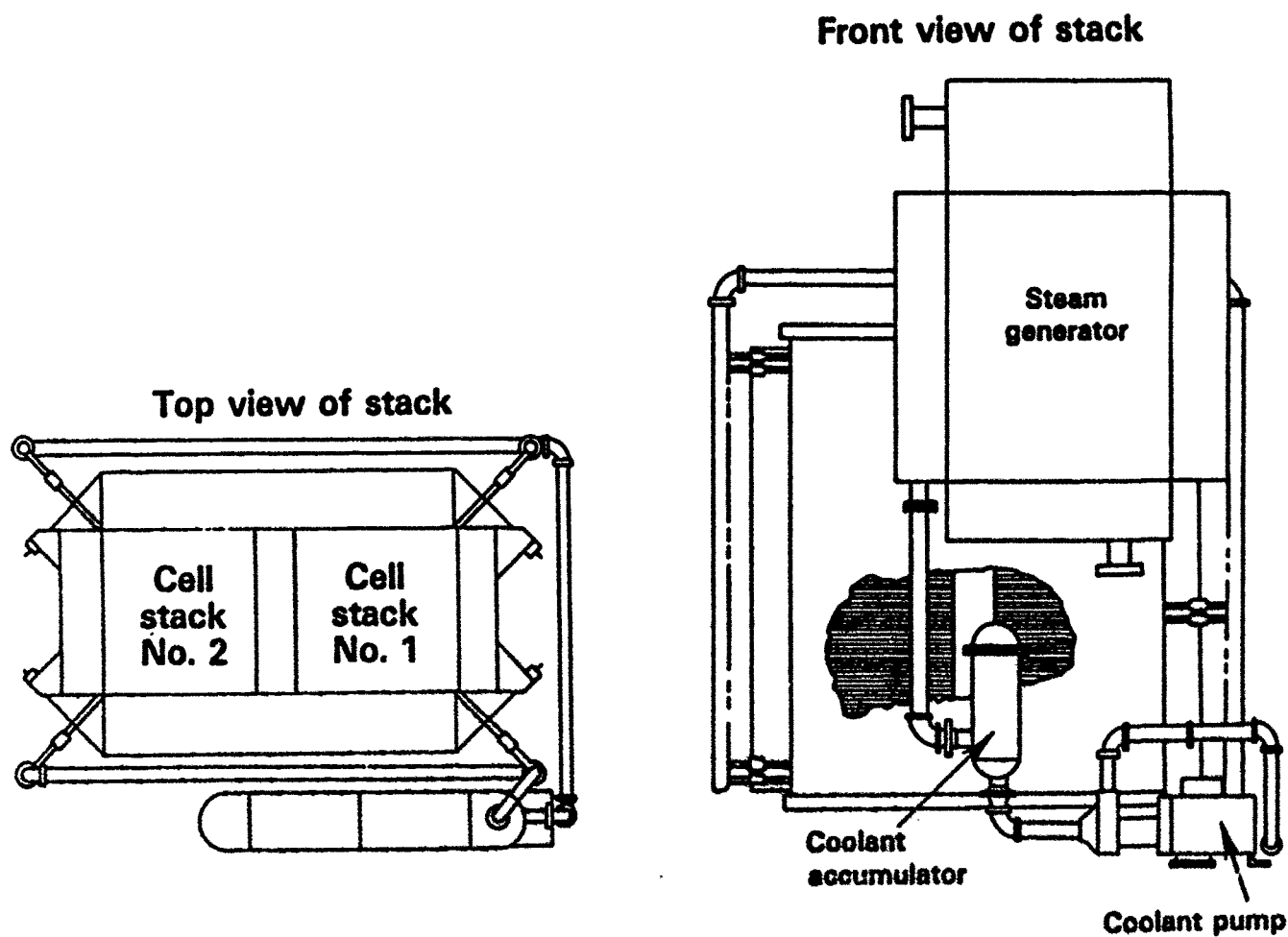


Figure 4. Cyclic Reformer Schematic

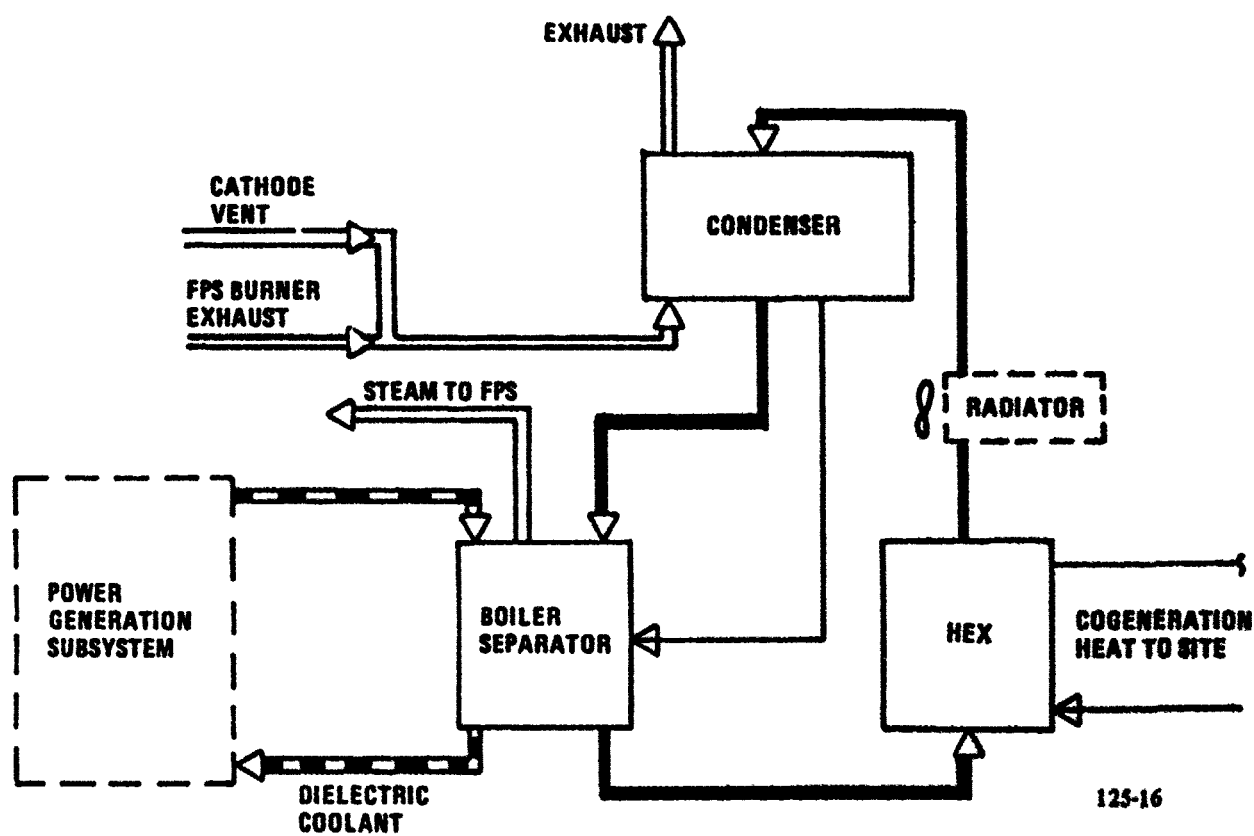


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Figure 5. Dual Stack Assembly Dielectric Cooling Loop

A schematic diagram of the thermal management subsystem is shown in Figure 6. The primary function of this subsystem is to remove waste heat from the fuel cell stack. The waste heat removed from the stack by the dielectric coolant is used to heat water and generate steam in the boiler/separator. In this manner the cell waste heat generates the steam required by the fuel processor. The balance of the waste heat is transferred to the water/glycol coolant. The water/glycol coolant transfers the heat to the cogeneration heat exchanger which makes the heat available for use at the site. When necessary, residual heat is removed by the radiator which may be either air or liquid cooled. The water/glycol then flows through the condenser where it cools the fuel processor burner exhaust and cathode vent gas. The water recovered from the exhaust gases is converted to steam as required by the fuel processor.

The temperature, pressure, flow rates, and composition at primary stations throughout the system are listed on Table 1 for rated power conditions and are located and identified on Figure 7 and drawing FC7660, sheets 1 and 2 (submitted separately).



125-16

Figure 6. Thermal Management Subsystem

Power Plant Physical Description

The conceptual arrangement of components for the 100 kW power plant is illustrated in Figure 8 and the power plant layout. The components are mounted on a base with provisions for lifting or sliding the power plant. The package size is 8' wide, 8' high, and 11.75' long. The total assembled weight is 14,500 lb.

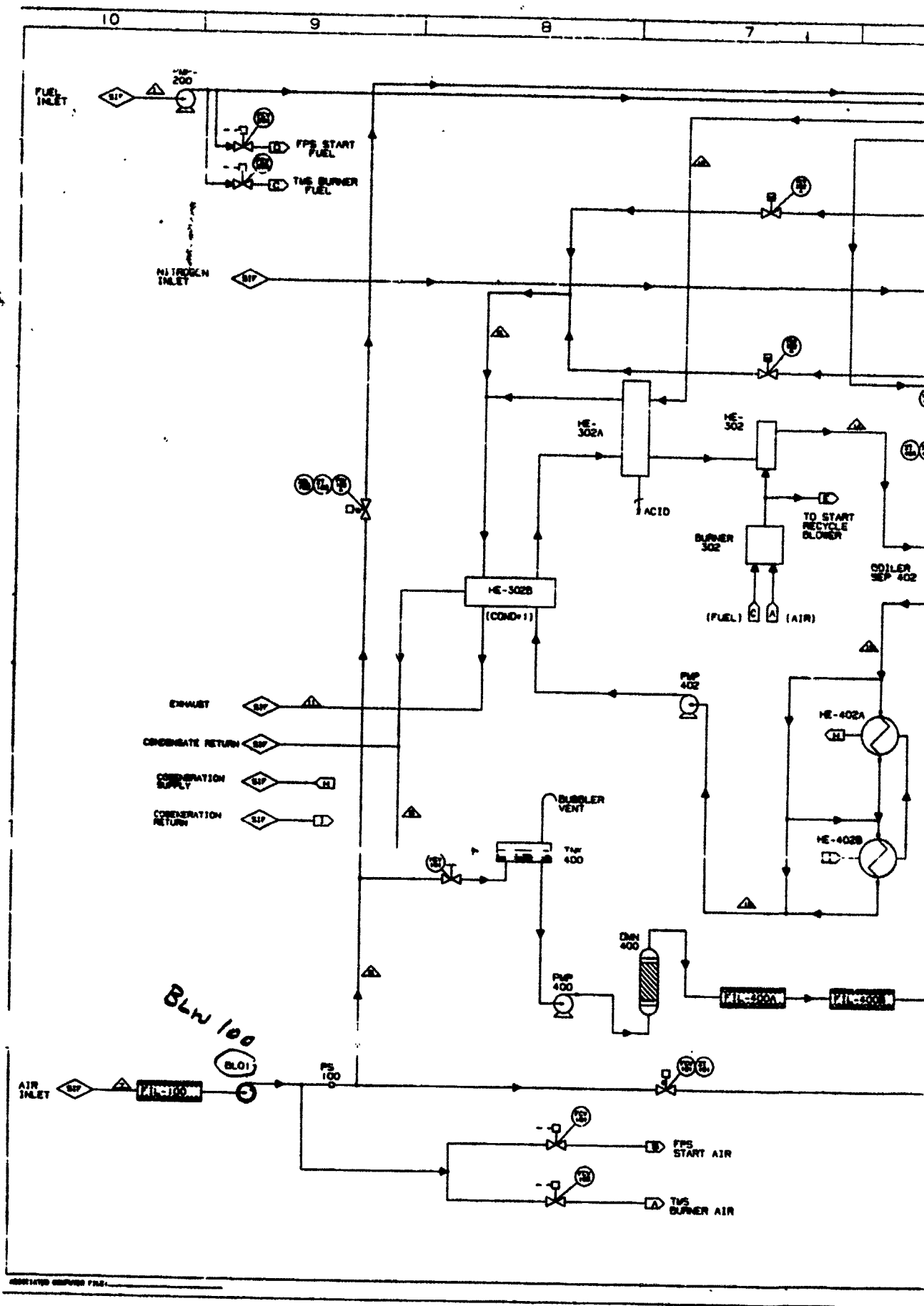
Power Plant Performance

The power plant is designed to produce 100 kW of AC power and operate on DFA diesel fuel. At the rated power conditions, the thermal efficiency is 41% and the fuel consumption is 46 pounds per hour (6.5 gph).

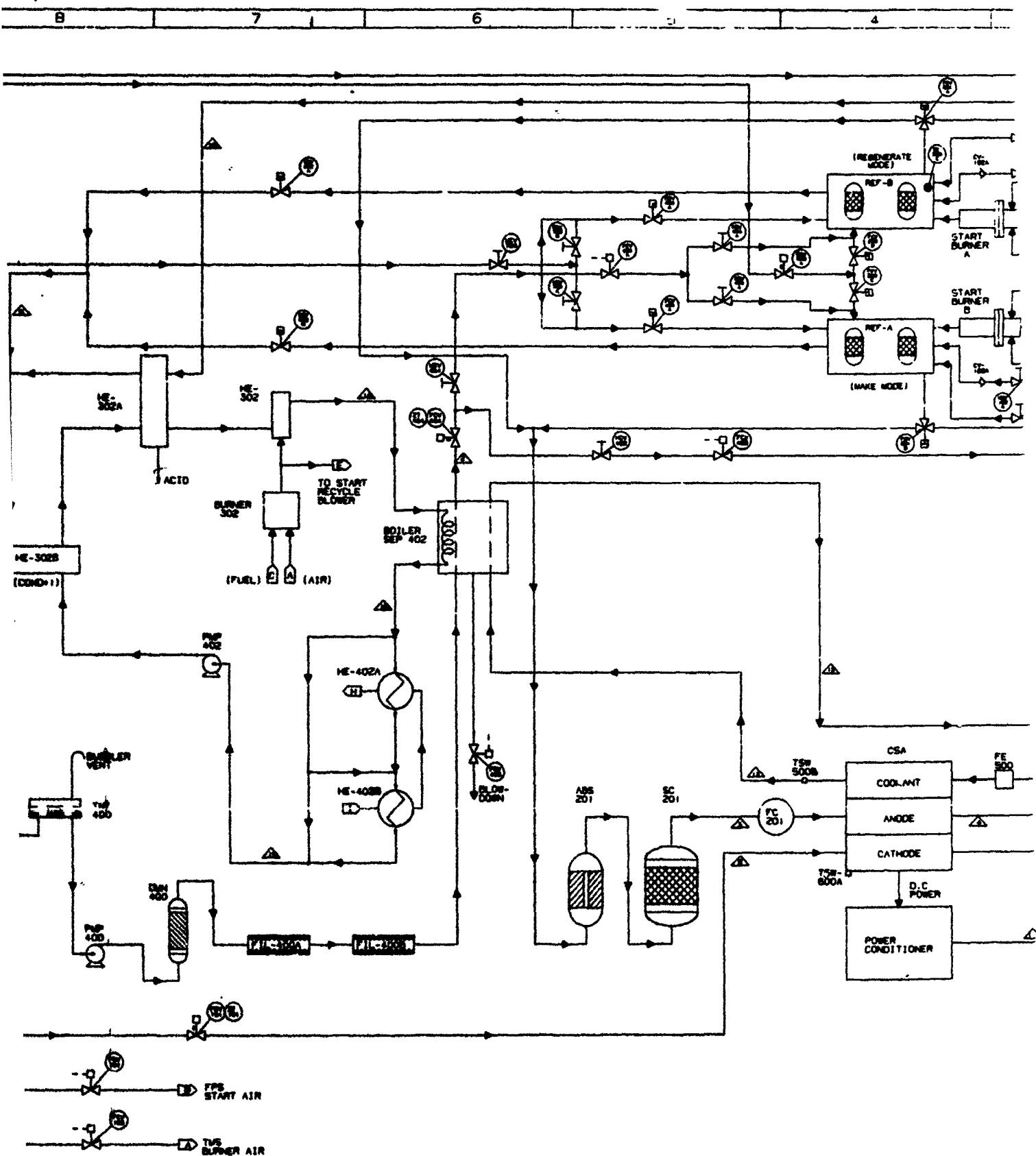
The fuel cell power plant has excellent part power performance. The estimated efficiency does not drop off until the output has been reduced to less than 50% of the rated output. The estimated thermal efficiency and fuel consumption, as a function of rated power, are shown in Figures 9 and 10.

The power plant is designed with provisions to provide cogeneration heat to the site. At rated power, the potential cogeneration heat available is over 400,000 Btu/hr with an overall thermal efficiency of 89%. The overall efficiency decreases slightly as power is reduced as shown in Figure 11.

The performance estimates and output are based on the operation at sea level on a 95°F day. The DFA diesel fuel specifications are listed in Table 2. These estimates are based on the typical lower heating value for fuel of 18,400 Btu/lb.



108 3



Power Plant Physical Description

The conceptual arrangement of components for the 100 kW power plant is illustrated in Figure 8 and the power plant layout. The components are mounted on a base with provisions for lifting or sliding the power plant. The package size is 8' wide, 8' high, and 11.75' long. The total assembled weight is 14,500 lb.

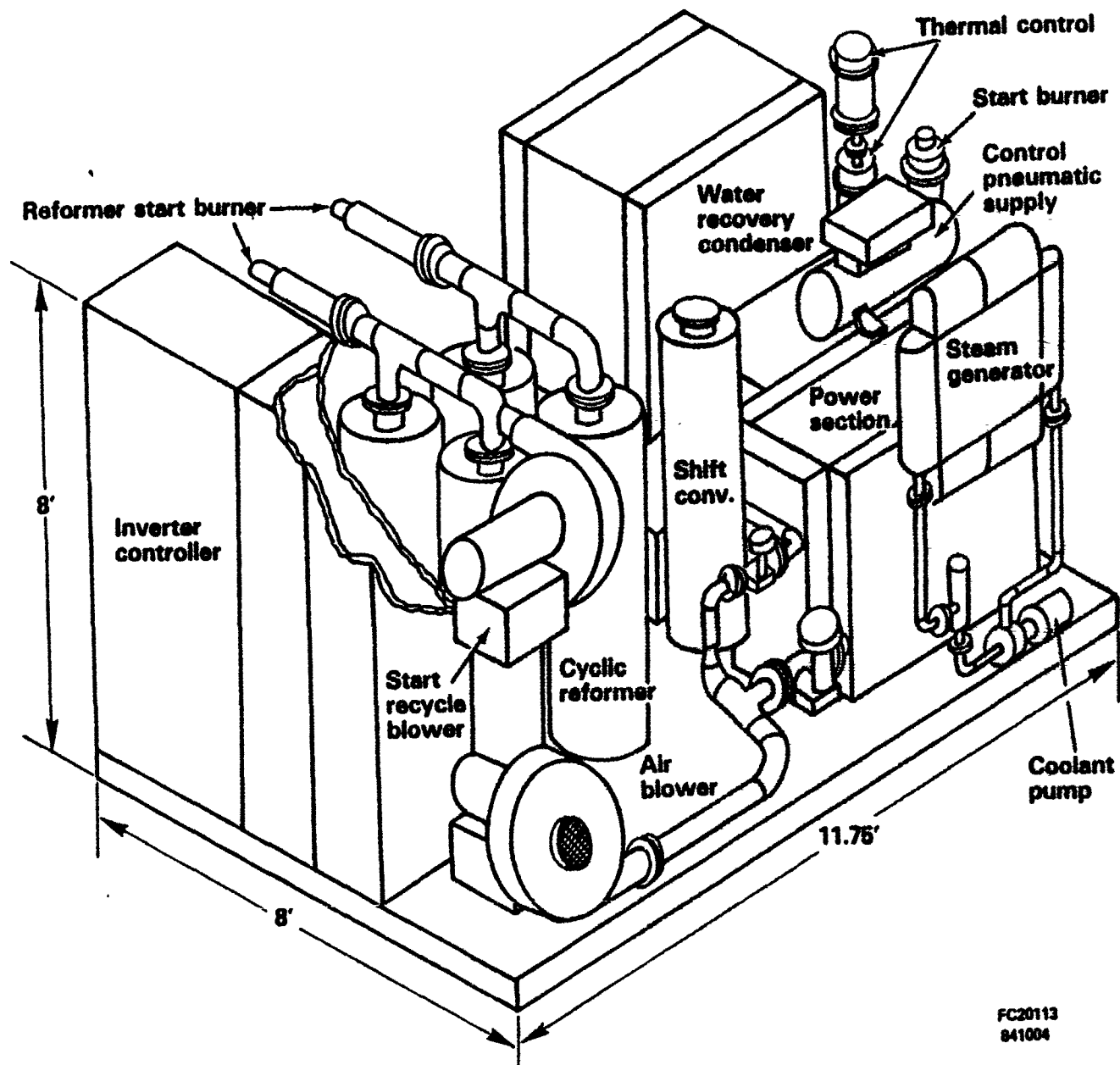
Power Plant Performance

The power plant is designed to produce 100 kW of AC power and operate on DFA diesel fuel. At the rated power conditions, the thermal efficiency is 41% and the fuel consumption is 46 pounds per hour (6.5 gph).

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Figure 8. Sketch of Remote Site 100-kW Power Plant

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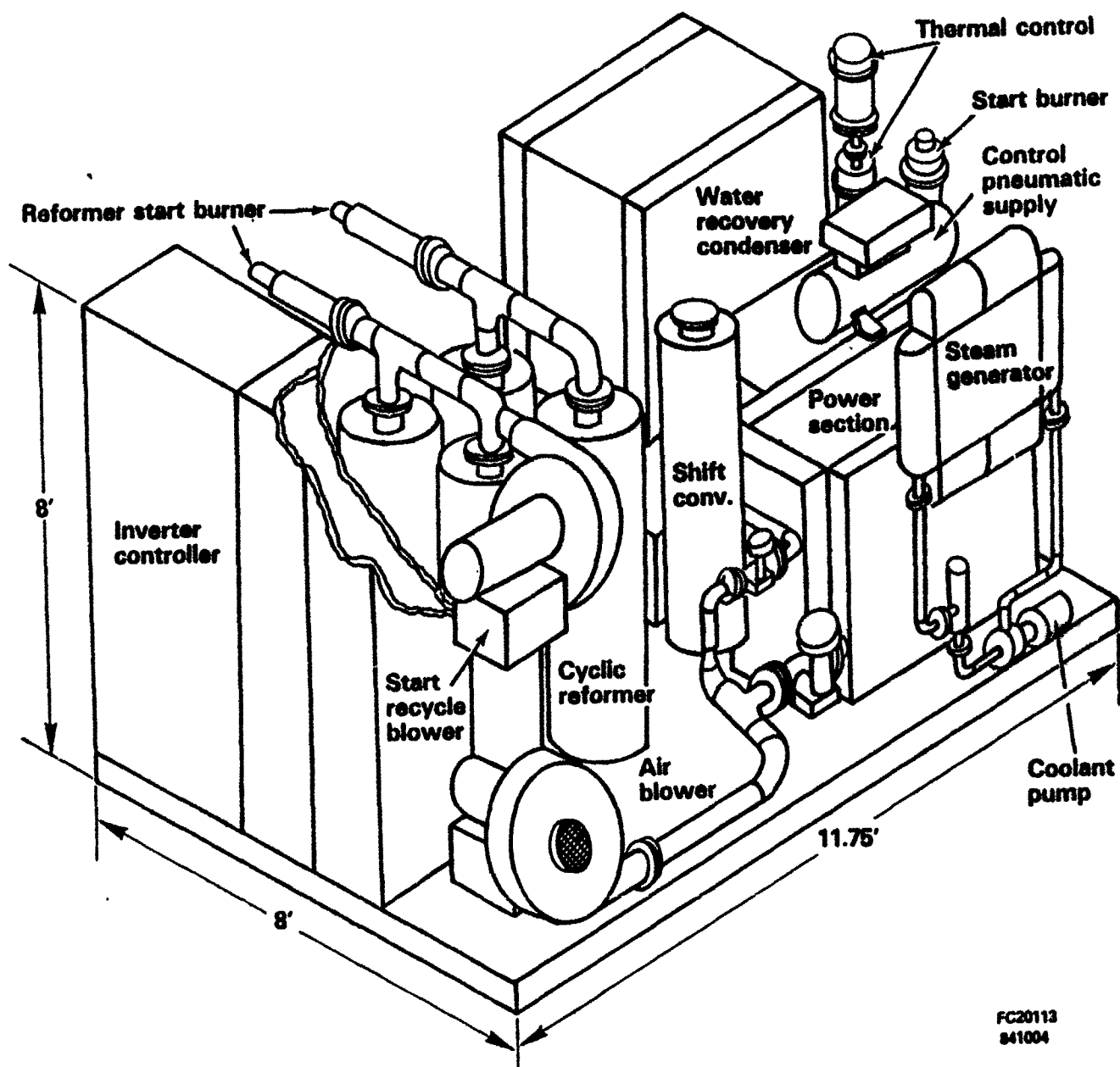


Figure 8. Sketch of Remote Site 100-kW Power Plant

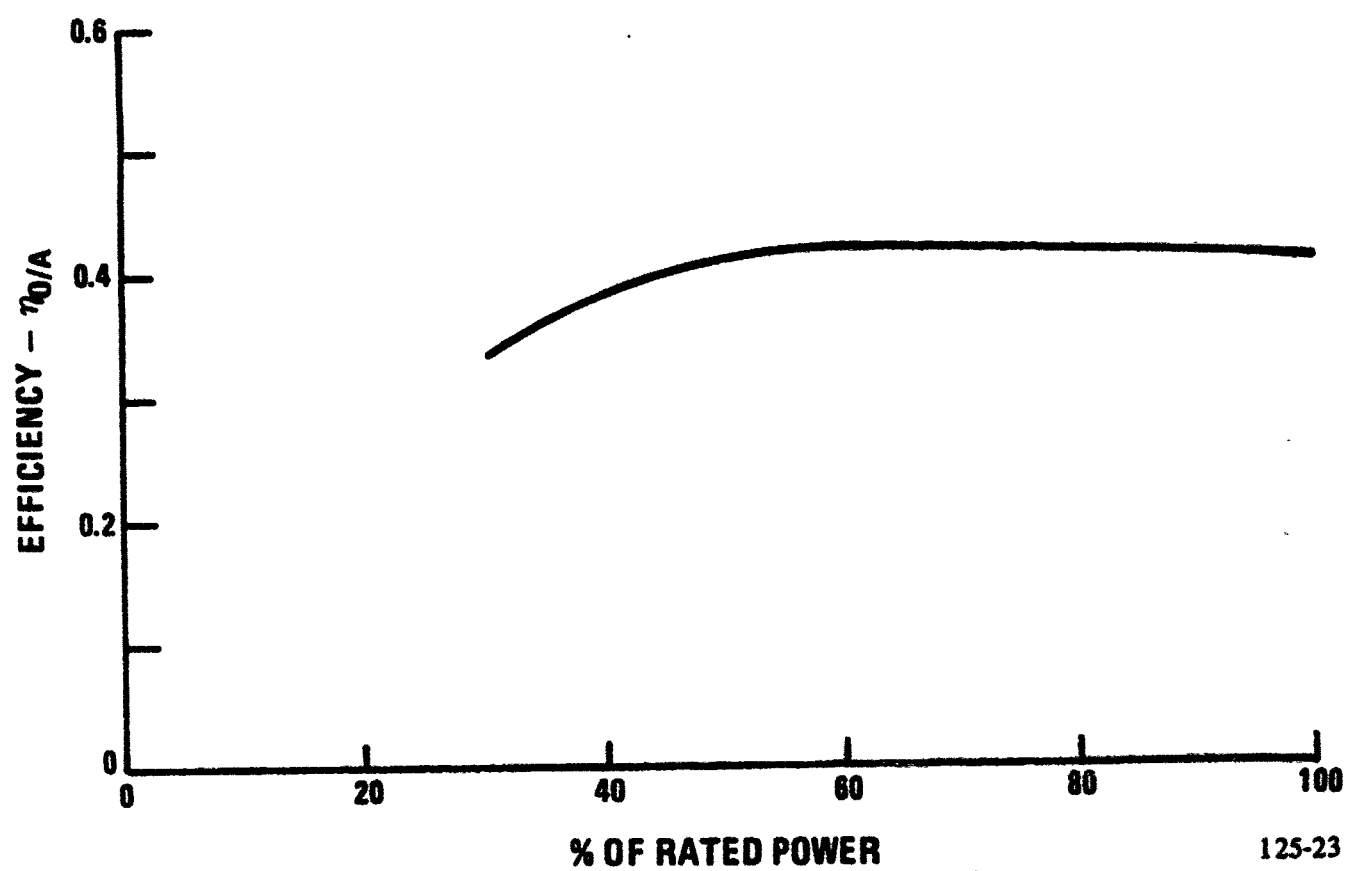


Figure 9. Power Plant Efficiency (Based on LHV)

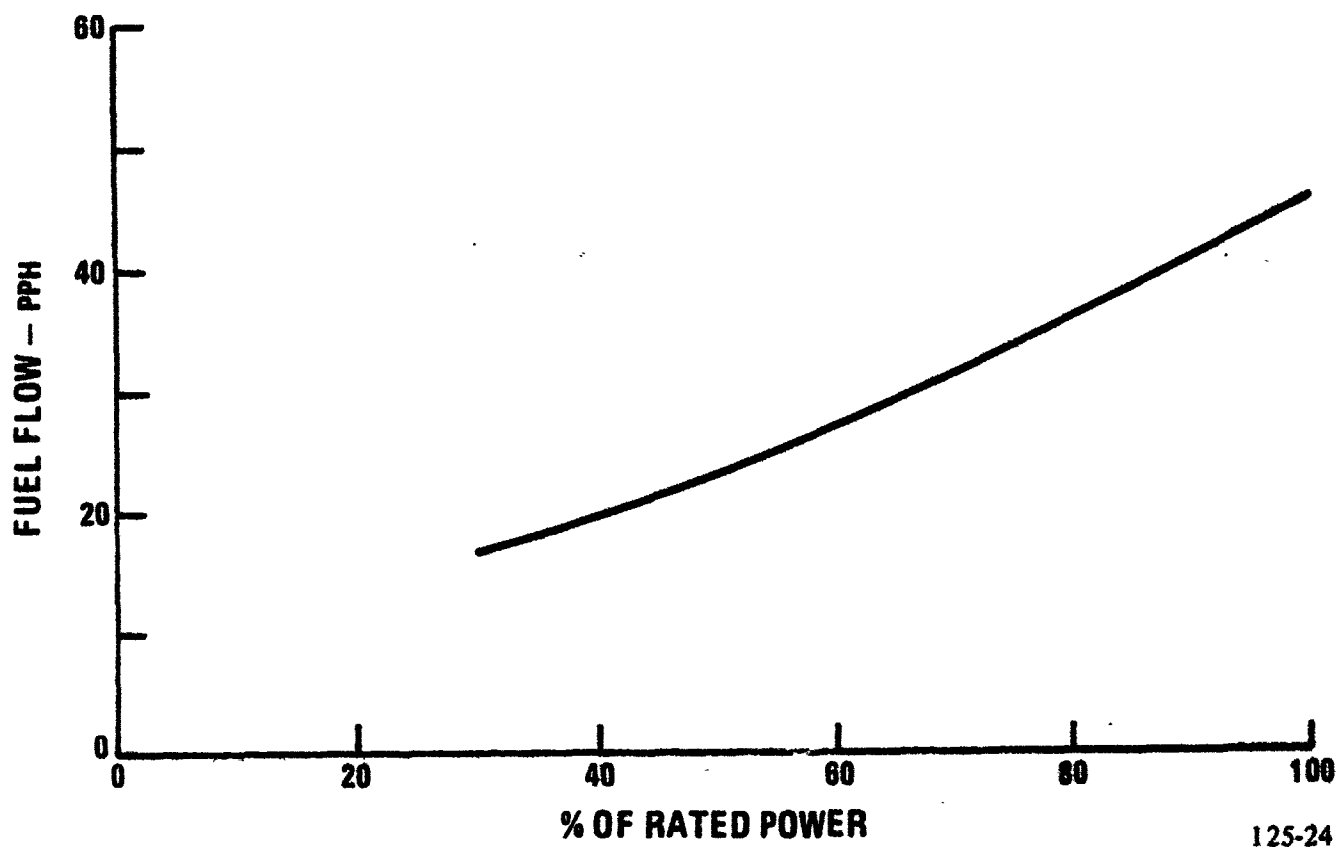


Figure 10. Power Plant Fuel Consumption

ENVIRONMENTAL TOLERANCE

The power plant will be capable of operating at ambient temperatures from -25°F to 120°F, altitudes from sea level to 6000 ft, and relative humidities from 10 to 100% without special equipment. It will withstand storage temperatures down to -65°F with the water system drained. The stack coolant system does not need to be drained.

Emissions from the power plant are low. The estimated number is less than 0.02 lb per million Btu, particulates less than 0.000003 lb/mm Btu, and has total hydrocarbon less than 0.02 lb/mm Btu. There will be no smoke and the SO_x will be in the range of 50 to 90% of a conventional diesel power plant depending on the amount of sulfur absorbed on the catalyst during the reformer make cycle.

The noise level 15 feet from the power plant should not exceed 60 dbA, and there will be no power plant generated vibration by the transmitted to the facility.

Table 2 Fuel Specification DFA Diesel Fuel

Flash Point °C Min.	38
Kinematic Viscosity @ 40°C CST	1.1 to 2.4
Distillation °C	
90% Evaporated Max.	288
End Point, Max.	300
Residual vol. %, Max.	3
Carbon Residue on 10% Bottom, Mass %, Max.	0.1
Sulfur, Mass %, Max.	0.25

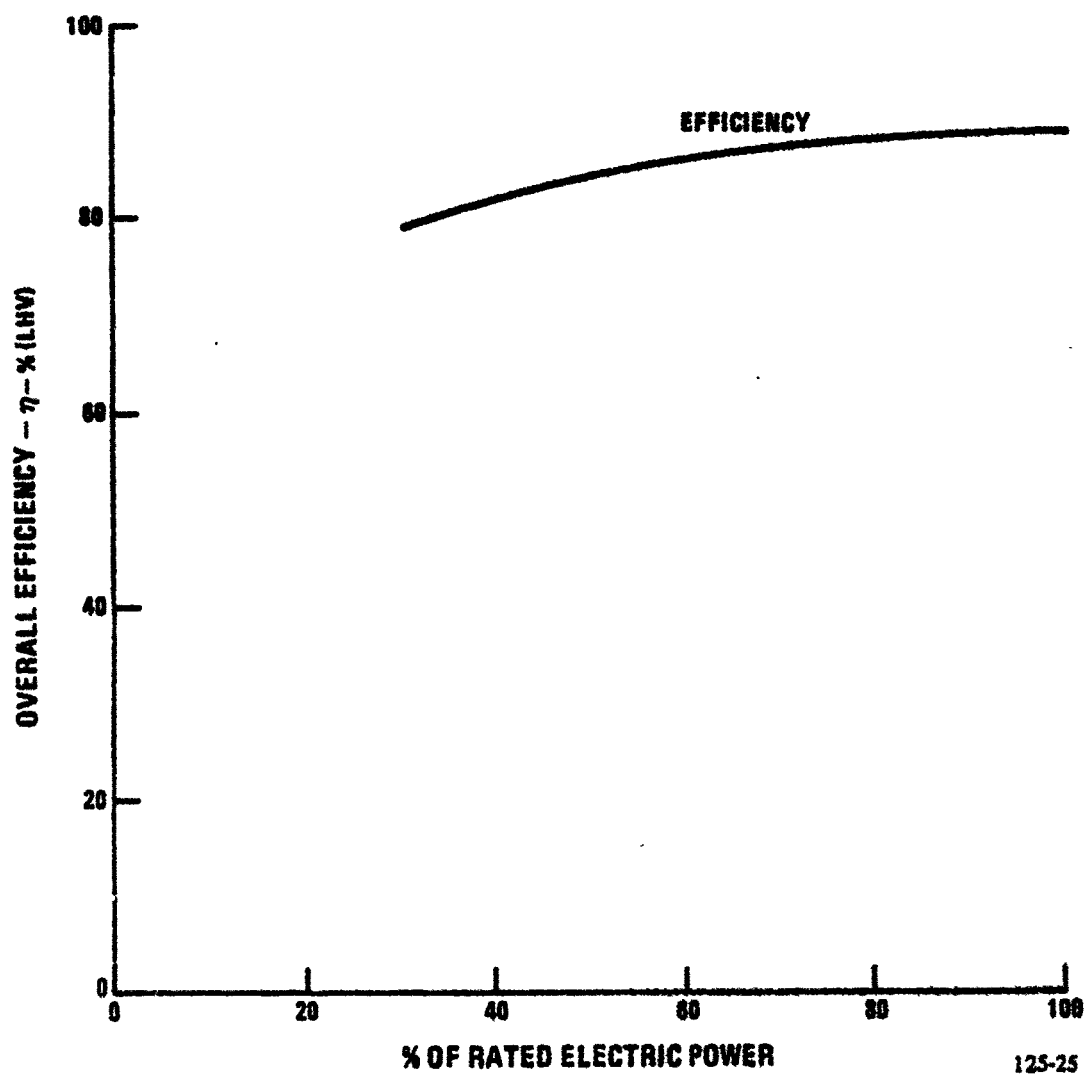


Figure 11. Power Plant Overall Efficiency with Cogeneration

Power Plant Size and Weight

The weight and volume breakdown for the 100 kW sited/transportable power plant is presented in Table 3.

Table 3. Weight and Volume Breakdown for Power Plant

	<u>Weight (Lb)</u>	<u>Volume (Ft³)</u>
1. Inverter/Controller	1,500	8
2. Fuel Processor	4,440	142
3. Power Section	3,400	95
4. Thermal Management	1,500	11
5. Air Supply	300	38
6. Heat Recovery	400	9
7. Structure/Piping/Wiring	3,000	281
TOTAL	14,500	752

This size is consistent with the specific volume (ft³/kW) UIC 40-kW On-Site power plant.

Transportability

The power plant has been packaged in order to make it readily transportable within the guidelines set forth in MIL-A-8421F. The following Table 4 delineates how the major transportation criteria are met.

Table 4. Major Transportation Criteria

	<u>FUEL CELL POWER PLANT</u>	<u>C-130H (CAPABILITY)</u>
Width	8'0"	8'9"
Length	11'9"	40'0"
Height	8'0"	8'6"
Weight	14,500 lb	43,399 lb
Volume	752 ft ³	2975 ft ³

The power plant will be constructed with a structural steel base frame. This will be provided with multiple hold down points matched to the grid pattern of the aircraft floor. Lift points will also be provided integral with the base structure and would provide alternate hold down points. With a physically stiff base structure and a floor area of 94 ft², the modular power plant will be capable of handling on all types of roller conveyor configurations and will yield a floor loading of 154 lbs/ft² on the aircraft freight deck.

All components will be rigidly attached to the structural base frame thus making the power plant capable of withstanding the specification transportation and handling loads. These loads are listed below.

G" force	Fore	3G
	Aft	1½G
	Lateral	1½G
	Up	2G
	Down	4½G

The on-site power plant design method for handling loads has been demonstrated with actual power plant shipments with trucks, aircraft and ship.

PRODUCT ASSURANCE STUDIES

Product Assurance studies were conducted to aid the design in safety critical areas and to estimate system reliability and power availability.

These studies included:

- o Preliminary Hazard Analysis - to identify appropriate design criteria for safety critical areas.
- o Reliability Assessment - to estimate the system's Mean-Time-Between Failure (MTBF).
- o Maintainability Assessment - to estimate the system's outage times.
- o Availability Calculation - to estimate the system's power availability potential.

Preliminary Hazard Analysis

The Preliminary Hazard Analysis (PHA), defined by Mil-Std.-882A, was performed to obtain an initial risk assessment of the fuel cell system. Its purpose was to identify safety-critical areas, evaluate hazards and identify appropriate safety design criteria. The PHA was performed early in this program so that safety considerations could be included in tradeoff studies and design alternatives.

The PHA, which was issued under a separate cover as FCR-6496D, evaluated all potentially hazardous conditions associated with the proposed design for severity, probability, risk and operational constraints. Safety provisions and alternatives to eliminate or control hazards were presented, and it was concluded that all identified hazards were adequately controlled by inherent, engineered and/or administrative features.

Individual Power Plant Reliability Assessment

The shutdown failure frequency for a 100 kW Remoted Sited/Transportable Fuel Cell Power Plant was estimated to be 4.3 failures per year. This corresponds to a Mean-Time-Between Failure (MTBF) of 2040 hours.

To obtain the 100 kW system failure rate, the system's reliability-critical components were identified. Reliability-critical components were those whose failures could, in a reasonable likelihood, result in a power plant shutdown.

In addition to UTC experience, published sources of component failure rates were consulted in order to assign failure rates to the identified reliability-critical components. The following published sources were used in assigning failure rates.

- o NUREG/CR-1635 - Nuclear Plant Reliability Data System 1979 Annual Reports of Cumulative System and Component Reliability.
- o IEEE Std 500 - IEEE Guide to the Collection and Presentation of Electrical, Electronic and Sensing Component Reliability Data for Nuclear-Power Generating Stations.

Table 5 shows typical component failure rates used in this analysis.

The failure rates for the reliability-critical components were then combined to estimate a total power plant shutdown rate of 490 failures/ 10^6 hours or 4.3 failures per year.

Table 5. 100-kW Remoted Site/Transportable Power Plant
Typical Component Failure Rates

<u>Component</u>	<u>Failure Rate Failures/10⁶ Hours</u>
Fluid Pumps	30 - 50
Control Valves	10
Blowers	8
Relief Valves	8
Heat Exchangers	7
Sensors	2 - 3

Maintainability Assessment

The average annual maintenance outage time for an individual Remote Sited/Transportable Fuel Cell Power Plant was estimated to be 172 hours. This estimate included consideration for both scheduled and unscheduled activities.

Estimates of schedule maintenance task intervals and time-to-accomplish were based on:

- o State-of-the-Art component and process technology,
- o UTC field and test experience
- o Requirements for minimum expendable item life, and
- o Preliminary power plant packaging schemes.

Scheduled maintenance tasks are shown on Table 6.

Three types of scheduled maintenance tasks were anticipated.

- o Replacement of minor expendable items such as air filters and cleaning of condenser fins for which power plant shutdown is not necessary.

- o Replacement of minor expendable items such as water filters, flushing of the water tank and inspection of steam system components for which power plant shutdown is required, and
- o Replacement of major items such as catalyst and the fuel cell stack and miscellaneous otherwise minor items for which power plant shutdown is required.

Scheduled maintenance tasks for each installed power plant averaged over a five year period were estimated to require 72 hours of planned outage per year.

Table 6. Typical Power Plant Scheduled Maintenance

REQUIREMENT	POWER PLANT WHILE OPERATING	ANNUAL SHUTDOWN
<u>INSPECTION:</u>		
● INSPECT STEAM SYSTEM COMPONENTS PER CODES		△
● STEAM SEPARATOR INTERNAL INSPECTION PER CODE		△
<u>CLEANING:</u>		
● CONDENSER HEAT EXCHANGER FINS	△	
● FLUSH WATER TANK		△
<u>REPLACEMENTS:</u>		
● PROCESS AIR BLOWER FILTERS	△	
● ELECTRONIC EQUIPMENT COOLING AIR FILTERS	△	

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Unscheduled maintenance are tasks to repair failed components. The power plant's estimate of unscheduled maintenance time or forced outage hours was derived from component failure rates and estimates of the mean corrective times.

The mean corrective time is the time required to repair a failed component and includes time to cool down, diagnose, remove/replace/repair, align/calibrate, check-out and restart. Based on UTC field and test experience and preliminary power plant packaging, the components' mean corrective time presented in Table 7 were developed. The failure rates presented were those discussed in the Reliability Assessment section above.

Weighting each components mean corrective time by its failure frequency allowed the power plant's mean corrective time to be estimated at 24 hours.

With an expected 4.3 failure/year, the forced outage time per year was estimated at 100 hours.

Table 7. Power Plant MCT

Component Type	Failure Rate (Yearly) (Total for all of this type)	MCT (Component)	Failure Rate X MCT
Valves	1.8	24	43.2
Pumps	0.8	24	19.2
Inverter/Controller	0.8	24	19.2
Sensors	0.5	8	4.0
Heat Exchangers	0.2	24	4.8
Blowers	0.1	24	2.4
Stack	<u>0.1</u>	72	<u>7.2</u>
	4.3 failures/year		100.0
$\text{MCT (power plant)} = \frac{\text{Failure Rate X MCT}}{\Sigma \text{ Failure Rates}}$			
$\text{MCT (power plant)} \approx 24 \text{ hours/year}$			

System Power Availability

A system configuration of five (5) parallel-connected 100 kW power plants was selected for the Remote Site application. This system configuration is predicted to achieve power availabilities of

- o 99.99% for tactical (100 kW) power, and
- o 99.7% for maximum (375 kW) power.

A power plant's reliability is given by the equation

$$R_{\text{power plant}} = 1 - \frac{\text{FOH}}{8760}$$

where FOH is forced outage hours per year as described in the maintainability assessment section. Using this equation the 100 kW power plant has an estimated reliability of 98.8%.

In order to calculate the availability potential of the five power plant installation, the scheduled maintenance scenario was assumed to be that each power plant's annual 72 hour maintenance would be accomplished consecutively and an attempt would be made to generate power continuously. This situation results in a period of 360 hours (5 x 72) where only four power plants are available and all are required for maximum power. During the remaining 8400 hours, five power plants would be available.

The statistical values for system reliability when four and five power plants are available and four (maximum power) and one (tactical power) are required is presented in Table 8.

Table 8. Power Plants Required

<u>Power Plants Available</u>	<u>Four Maximum Power</u>	<u>One Tactical Power</u>
5	0.996	0.999
4	0.953	0.999

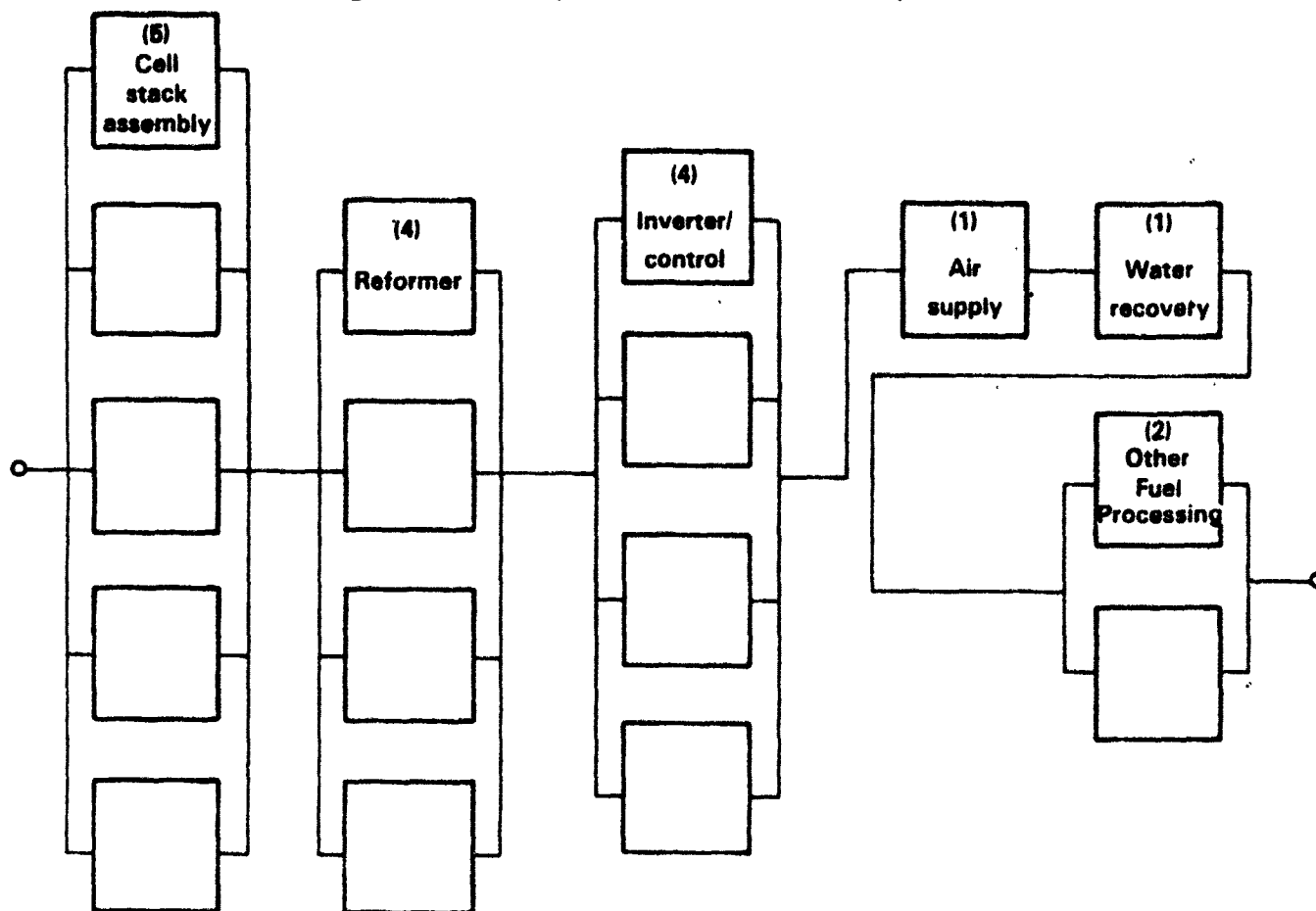
Other availability studies considered various combinations of individual power plants, and site integrated subsystems to achieve power and reliability requirements. The combinations of subsystems evaluated for site integrated power plants included

- o 4 to 5 cell stack assemblies,
- o 3 to 5 reformers,
- o 4 to 5 inverters,
- o 1 to 5 air supply subsystems,
- o 1 to 5 water recovery subsystems, and
- o 2 to 5 fuel processing subsystem.

Figure 12 shows the optimum installation configuration from these studies.

More recent availability studies reflected new directions which lead to individual power plants, air transportable via C130 aircraft, being grouped together to provide the required power with the appropriate availability. The availability calculation section above discusses the final system selected, (5) 100 kW power plants and compares the availability estimates for both maximum and tactical power in a 4 and 5 power plant system.

Site integrated subsystems for 375 kW prime power



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Figure 12. Power Plant Reliability Logic - Option 3

LIFE CYCLE COSTS

Introduction

The life cycle cost analysis was utilized to compare the costs of operating a diesel with fuel cell power plant for the SEEK IGLOO application. The comparisons included the effects of power plant efficiency, equipment costs, equipment reliability and maintainability.

The following section discusses the study results and the analyses that showed the fuel cell power plant to have a 24% life cycle cost advantage over the existing SEEK IGLOO diesel generating system.

Approach

A computer model was developed to evaluate life cycle costs for the sited/transportable power plant. The program also yielded life cycle cost data on the diesel power plants, currently installed at the SEEK IGLOO site, so that comparisons between the fuel cell and diesel power plants could be made on a consistent basis. The evaluation parameter used to compare the two power plants is the difference in the life cycle costs (Δ LCC) over the 20 year life of the power plants.

The life cycle costing methodology used in the computer program was based on the North Warning Life Cycle Cost Manual, January 1983. Costs were expressed in constant 1983 dollars, with no inflation, escalation, or discounting of money assumed.

Life cycle costs are comprised of the following major elements; operational costs, power plant acquisition costs, and maintenance costs. Operational costs include primary fuel charges (including transportation), costs of fuel required to supplement the thermal output of the power plant (if necessary to meet the total site thermal requirement), and the fuel charges associated with providing backup power. Acquisition costs include power plant capital cost, power plant installation costs,

and the costs of transporting the power plants to the site. Maintenance costs include the material and labor charges associated with both forced outage and the routine planned maintenance actions. For a fuel cell power plant this includes periodic replacement of the fuel cell stack.

Power Plant selling price was estimated by applying to the manufacturing cost a nominal manufacturer's mark-up of 50 percent which is derived from published government business statistics. The markup reflects the cost of such factors as marketing, engineering product support, taxes and profit.

Based on the Alaskan Air Command data, certain key assumptions were made pertaining to both the fuel cell and diesel power plants. Primary fuel costs were \$1.00/gal plus \$1.50/gal transportation with a total delivered fuel cost of \$2.50/gal. Supplemental fuel was estimated on the same basis. Maintenance labor rates were \$75/man-hour. Spare parts delivered to the site cost \$0.25/lb or \$2/lb if done on an emergency basis.

A number of major differences between the fuel cell and the diesel power plants were incorporated into the life cycle cost model. One area of difference was the installed power plant capacity. The SEEK IGLOO site is currently occupied by four, 250-kW diesel generators. Two of the units are operated on a continuous basis (at part load), while two units are kept as spares in a cold ready condition. This high level of redundancy is maintained to insure an overall power availability of 99%. Based on the reliability characteristics of the fuel cell power plant this level of overall power availability can be maintained with a much lesser degree of redundancy, (i.e., five 100-kW fuel cell power plants)

Results

A significant advantage in electrical efficiency, as shown in Figure 13, results in life cycle cost savings for the fuel cell vis. a vis. the diesel. This effect is more pronounced if the delivered fuel costs are higher than the study baseline (\$2.50/gal). These results are shown as Figure 14.

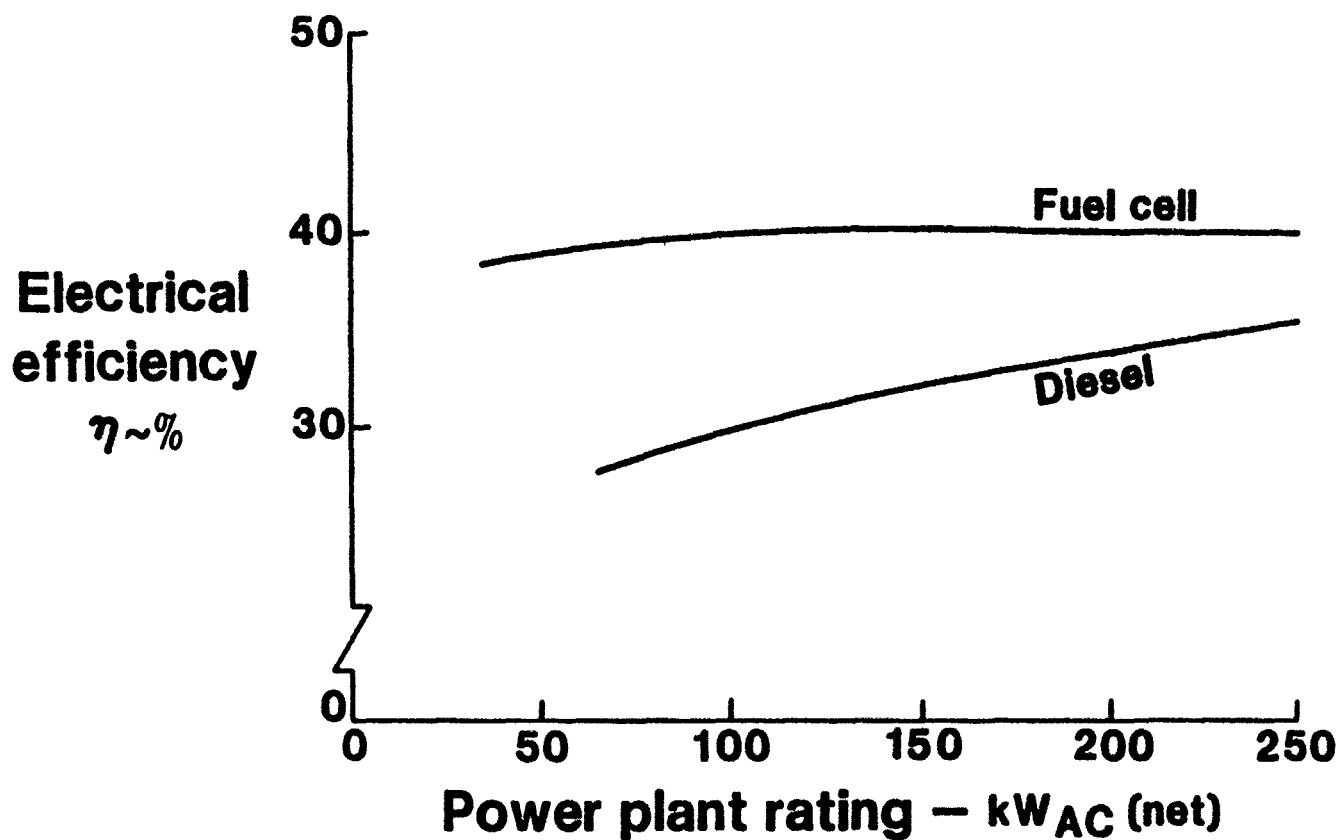
A base case comparison of the total life cycle costs of the fuel cell and the diesel is shown as Figure 15.

These results indicate a 24% advantage total life cycle cost for the fuel cell over the diesel for the base case conditions. This advantage is derived from a combination of factors; the high delivered fuel costs at the remote site, the high (40%) electrical efficiency of the fuel cell, and the lower maintenance requirements of the fuel cell relative to the diesel. The results are quite sensitive to the latter factor, as shown in Figure 16.

The base case assumes that the diesel power plants occupy 25% of a single operators time for maintenance. Due to the high labor rate at the remote site (\$75/man-hour) this has a significant effect over the 20 year life of the power plants.

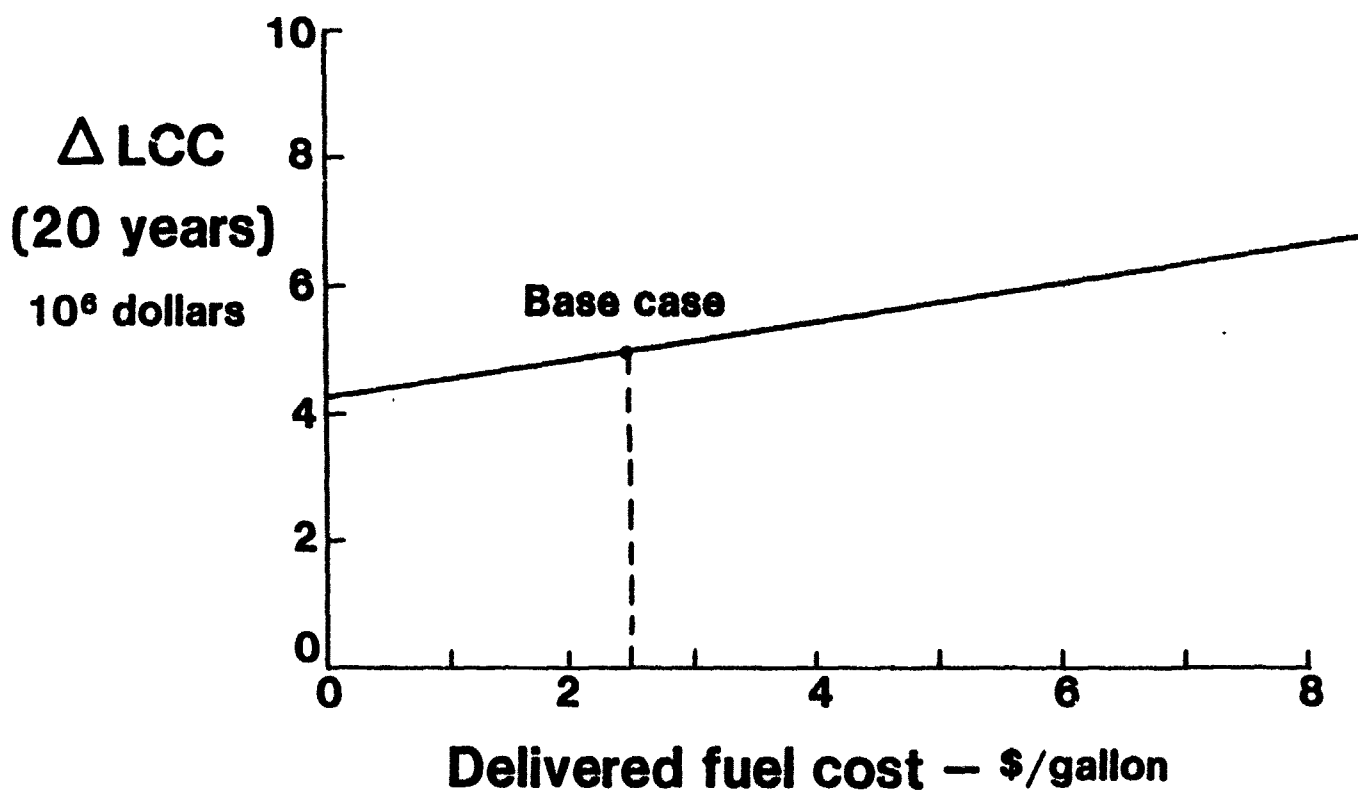
Another site specific variable that can impact the Δ LCC results is the site thermal to electric (T/E) ratio. This dimensionless parameter is the ratio of the average thermal requirement to the average electric requirement for the site. The specific SEEK IGLOO site used in this study had a T/E of approximately 1.4. As Figure 17 indicates, the advantage of the fuel cell would be further enhanced by lower site T/E ratios. This effect occurs due to the high electrical efficiency of the fuel cell, resulting in somewhat reduced thermal output relative to the diesel.

A final study performed was the impact of fuel cell unit size on Δ LCC. Fuel cell sizes in the range of 60-200 kW were considered. Although the base case size was selected as 100-kW, results indicate that minimum life cycle costs occur at the 200 kW size. Availability for the base case (5-100kW) is 99.7%, surpassing the goal of 99%. The results are summarized in Figure 18.



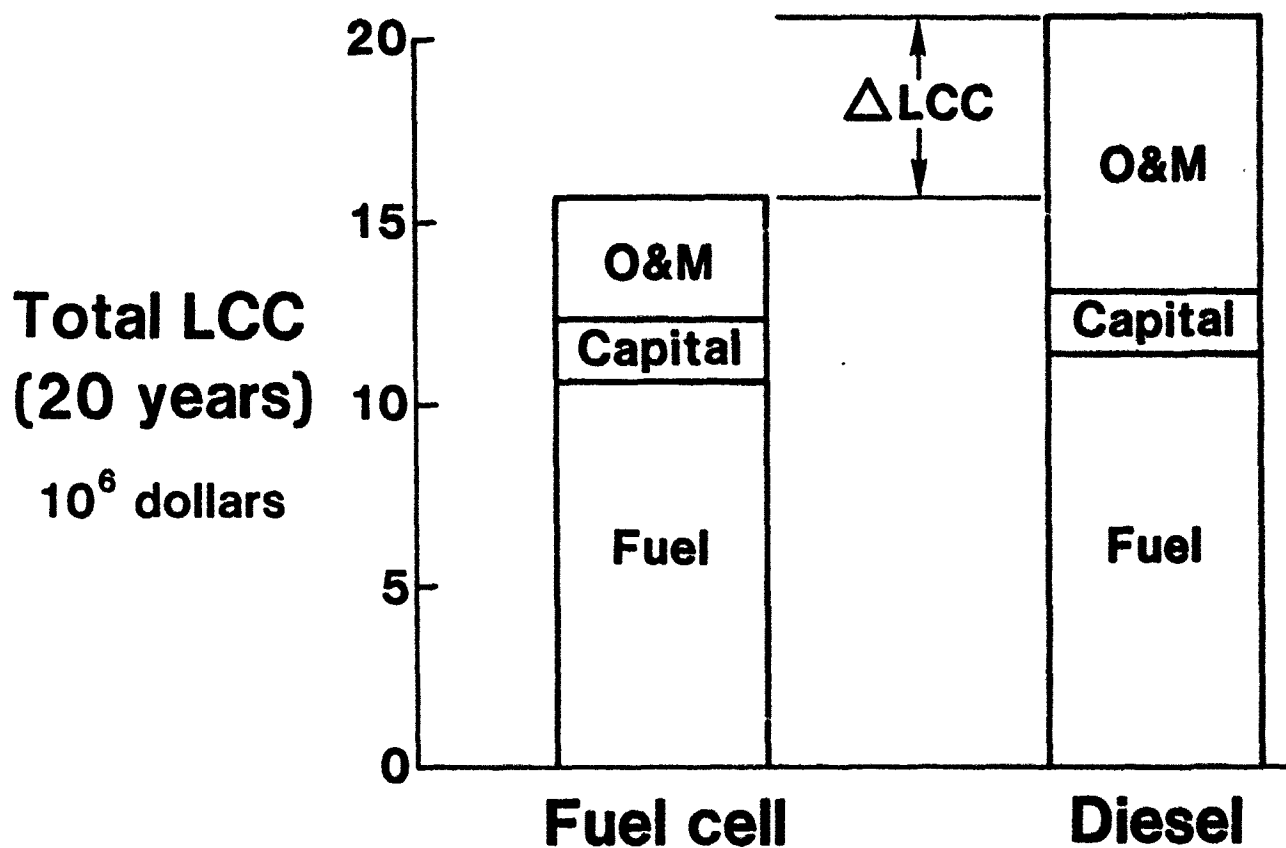
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Figure 13. Comparison of Fuel Cell and Diesel Electrical Efficiency



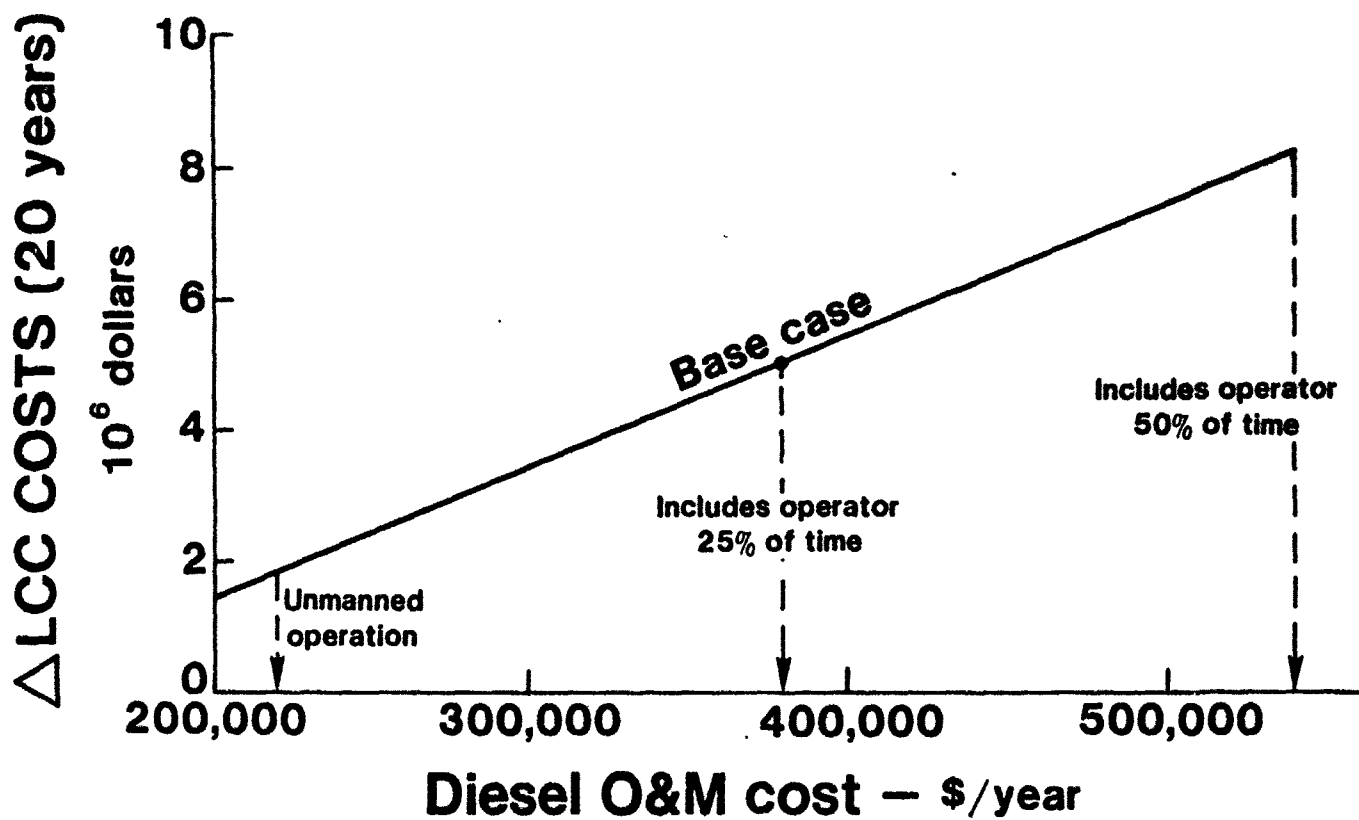
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Figure 14. Impact of Site Specific Variables



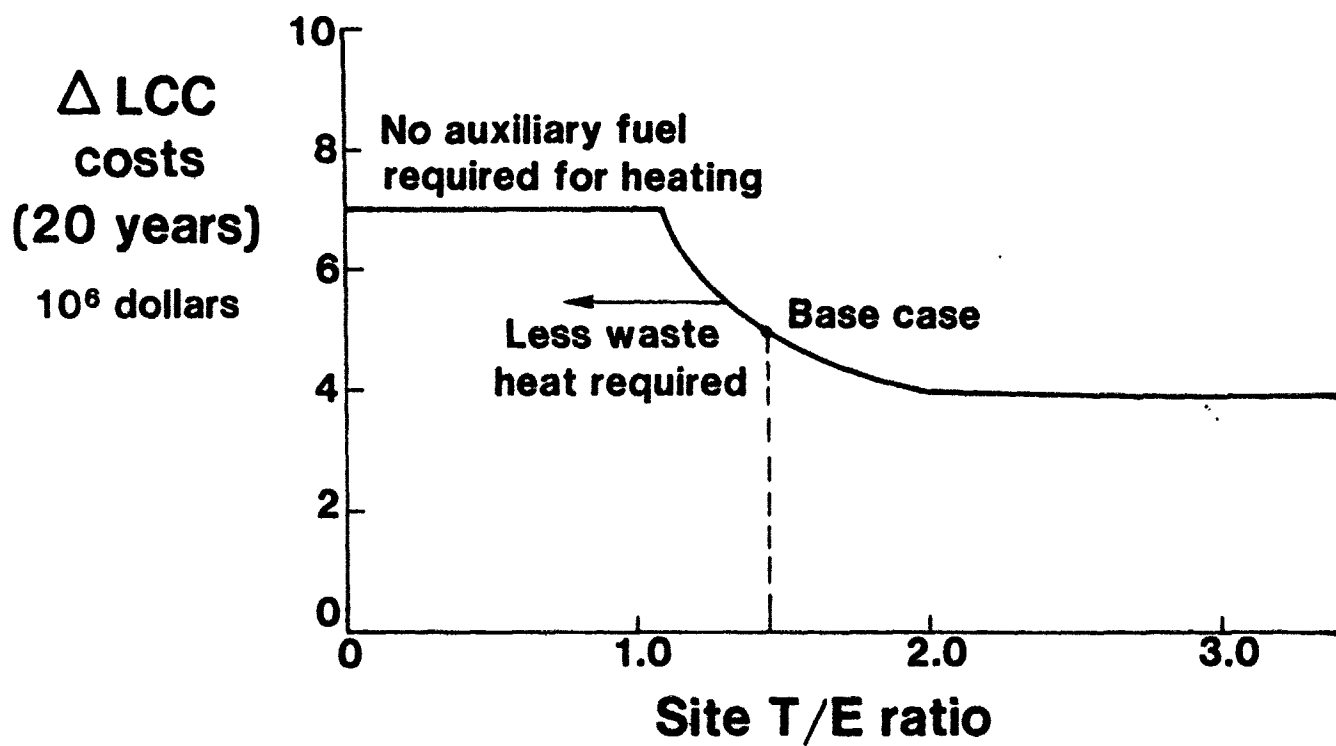
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Figure 15. Base Case Life Cycle Cost Comparison



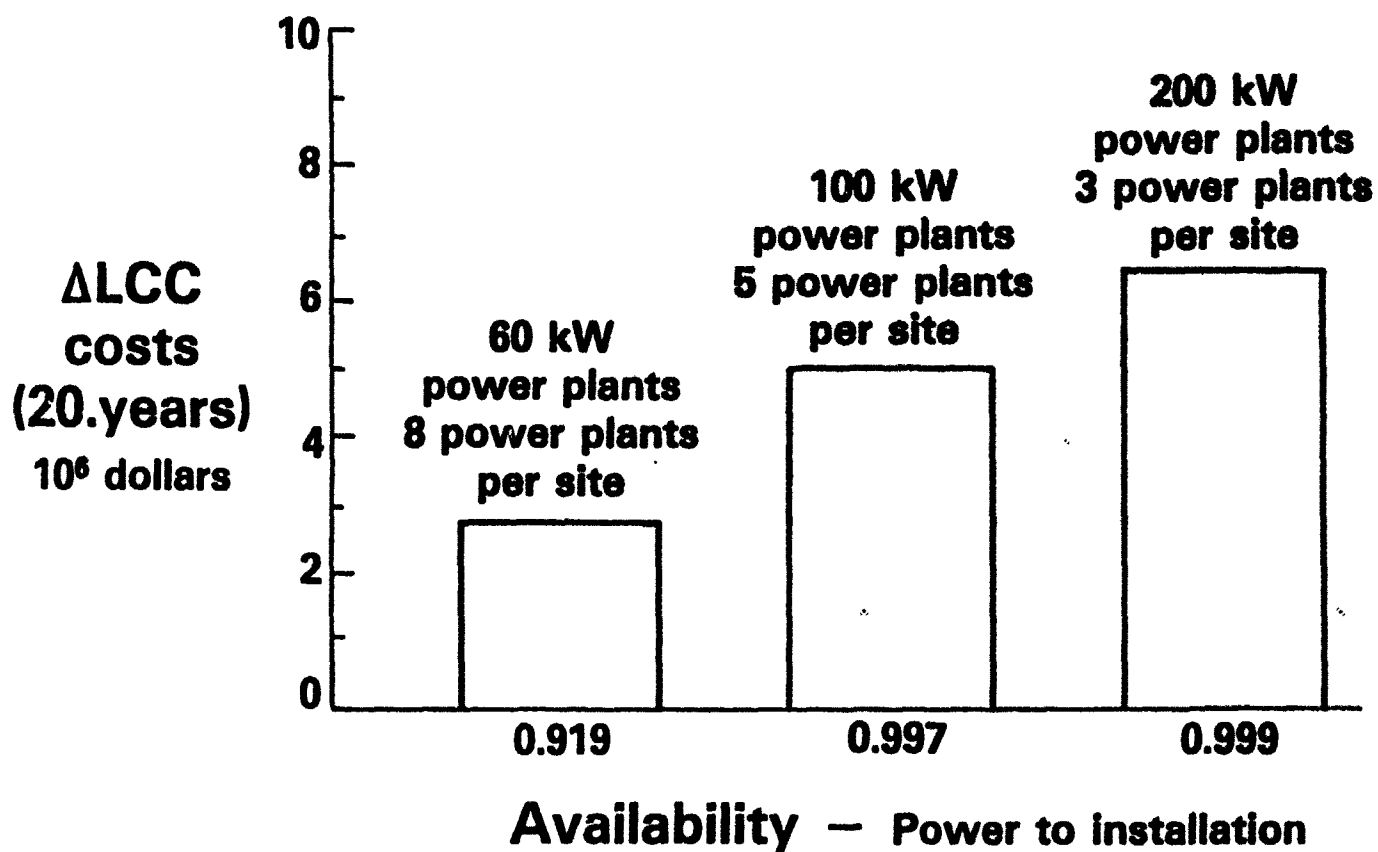
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Figure 16. Impact of Site Specific Variables



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Figure 17. Impact of Site Specific Variables



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Figure 18. Impact of Fuel Cell Power Plant Size

SECTION III

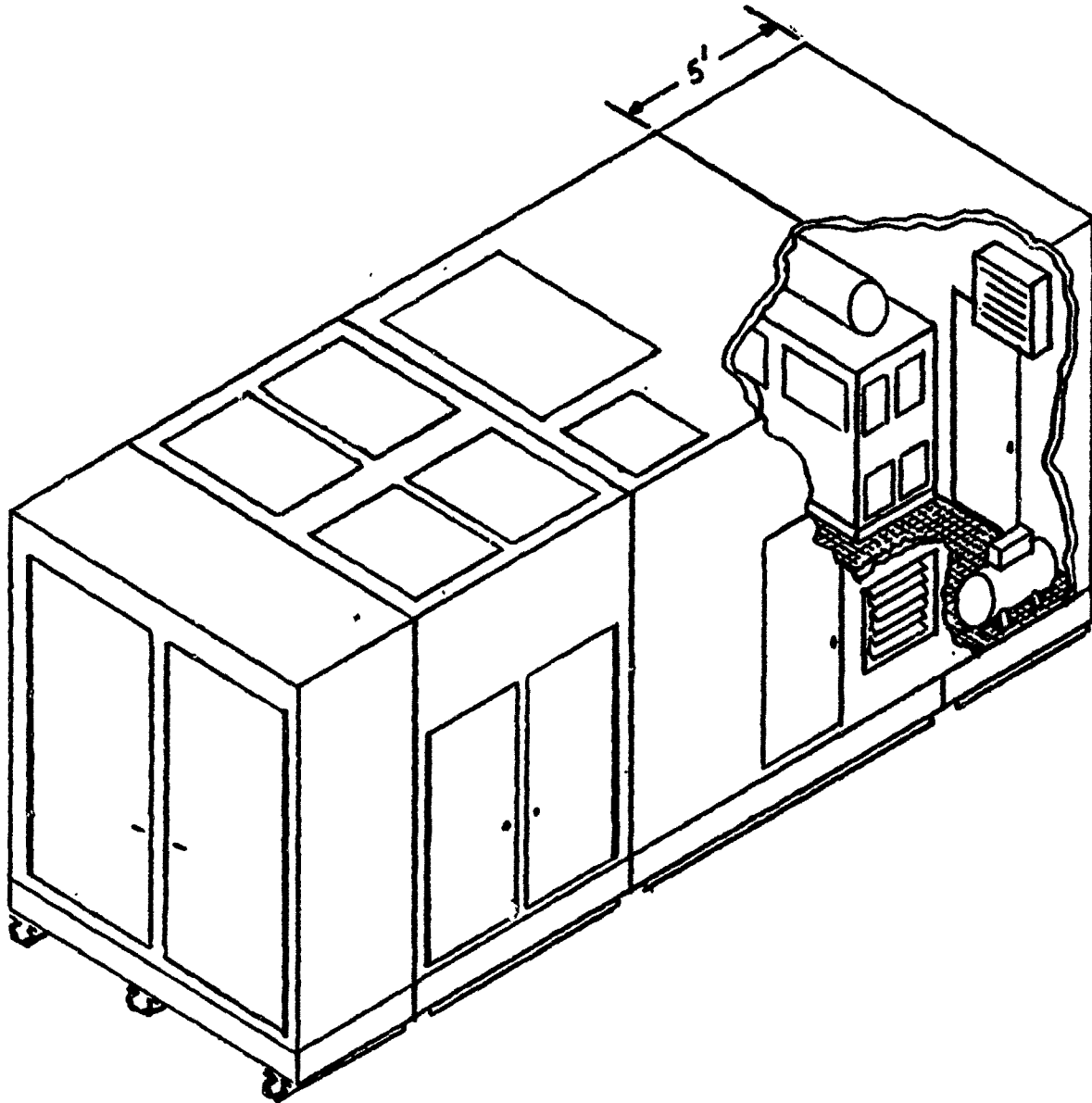
100-KW MOBILE FUEL CELL POWER PLANT

INTRODUCTION

A power plant design suitable for a mobile application power plant was studied and evaluated as in the conceptual design task. The approach taken in this subtask was to modify the sited/transportable power plant design to include an enclosure for weatherization, shock mount skids, and a source of electric power for starting the power plant under stand-alone field conditions. The power plant design is shown in Figure 19. After consultation with the Air Force it was decided to pursue the sited design as a baseline and study of the mobile application was discontinued after the conceptual design phase.

SYSTEM REQUIREMENTS

Design requirements for the Mobile Power Plant were derived from the Mil-Std 1332-B, Definitions for Classification of MEP Engine Generator Set Family, and Mil-G-52884-A, Generator Sets, DED 15-200 kW and Mil-Std 633E-30, MEP 100 kW Engine Driven Generator for the purpose of defining the fuel cell mobile power plant. A summary of MEP Engine Generator Set requirements utilized for the fuel cell conceptual design are summarized in Table 9.



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Figure 19. Mobile Electric Power 100 kW, 60 Hz,
Fuel Cell Generator Set

TABLE 9. MOBILE ELECTRIC REFERENCE (MEP-007A) POWER DIESEL
SPECIFICATION - 100-kW

Fuel Type	DF1, 2 & A Plus JP Fuels
Electrical Output	50/60 Hz, 120/208 V 240/416 V 30, 4 Wire
Overall Electrical Eff. (%)	28
MTBF (Hours)	580
Operation Type	Manned
Noise (DBA)	(85 DBA @ 25')
Environmental	-65 to 125°F
- Storage	-25 to 125°F
- Operation	-65 with Win./Kit
Altitude (Degrees)	Level to 15°
Handling Shock	10 MPH Rail Impact 12 In. Drop

SYSTEM DESIGN CONVERSION

The Mobile power plant design for fuel processing, power section and inverter were those for the Sited Transportable power plant, described in the previous section. Only minor design changes are required to adapt the Sited design to the Mobile application.

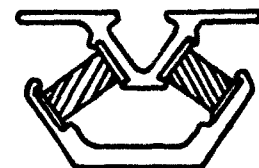
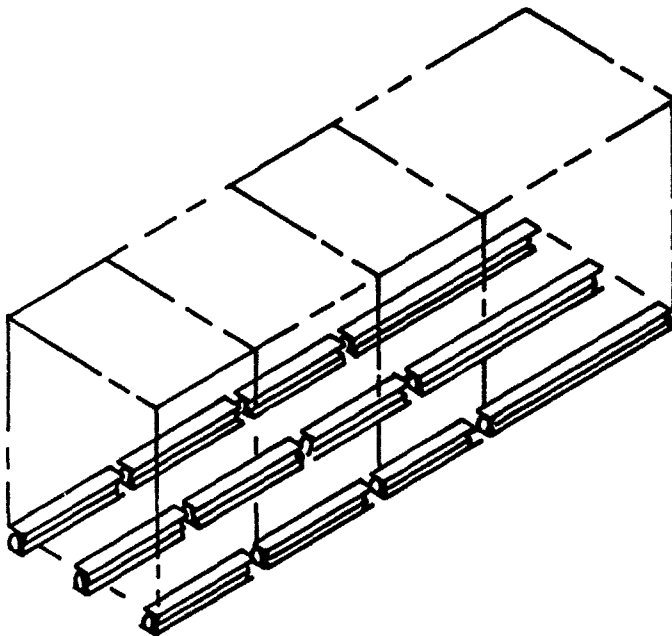
An insulated cover encloses the power plant to aid power plant starting at ambient temperatures down to -65°F and to contain a component surface temperature of over 32°F during operation. Included also within the power plant enclosure are provisions for providing the electric power required for power plant system pumps, blowers and electronic control devices that participate in the startup process. The

electrical requirements for the starting may be accomplished with a small electric generator set. A second design requirement affects the fuel system. The mobile Electric Power Plant system application requires a fuel day tank subsystem. Additional design modifications are necessary to make the power plant freeze-tolerant with water stored in the system. A freeze-tolerant water storage tank that includes an electric heater is required. The stored water is a fundamental requirement for fuel processing during start-up until product water is available from power plant on-load operation. Once the power plant is operating, power plant system temperatures within the enclosure will maintain the water tank and water containing components and piping above freezing.

Shock mounts are included to protect the power plant equipment when subjected to the MEP transportation load requirements. Commercially available shock mounts of the type shown in Figure 20 attached directly to the base pallet provide the shock protection required for handling and for field transportation.

Operator display and controls are built into the Mobile Power Plant to satisfy stand-alone requirements.

Shock mount sited/transportable power plant on mounts



**Shock mount
cross section**

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832707

Figure 20. Design Approach Shock and Rough Handling

FUEL CELL POWER UNIT CHARACTERISTICS

System Reliability

The mean time between failure for the Mobile Power Plant is affected by modifications required to make this power plant a stand-alone and self-starting unit. Added equipment to enhance subfreezing starting affects the reliability of the pneumatic compressor for the control system, electric heaters to heat water containing areas, equipment and components associated with the fuel supply system, and the water treatment components. The combined effects of the Sited, Transportable Power Plant design revisions to obtain a Mobile unit conversion result in a mean time between failure of 1700 hours. The availability for power plant rated power operation would be .964.

PRODUCT ASSURANCE STUDIES

Reliability Assessment

The shutdown failure frequency for an 100 kW Mobile Fuel Cell Power Plant is estimated to be 5.1 failures per year. This corresponds to a Mean-Time-Between-Failure (MTBF) of 1700 hours.

To obtain the Mobile Power Plant system failure rate, an analysis similar to that described in Reliability Assessment, Section 2, was performed. The only difference in the Mobile Power Plant analysis was the inclusion of additional components described in the System Design section above.

The same method as discussed in Maintainability Assessment, Section 4, was also used for unscheduled maintenance. However, since the Mobile Power Plant would be housed in an enclosure, a conservative 24 hours was added to the power plant's mean-corrective-time.

With an expected 5.1 failures/year, the forced outage hours per year was estimated at 245 hours. These components increased the power plant's failure rate from 490 failures/10⁶ hours for the sited/transportable to 585 failures/10⁶ hours or 5.1 failures per year.

Maintainability Assessment

The average annual maintenance outage hours for the Mobile Fuel Cell Power Plant was estimated to be 317 hours. This estimate included consideration for both scheduled and unscheduled activities.

Schedule Maintenance activities and times for the Mobile Power Plant are predicted to be the same as that of the Remote Sited/Transportable power plant discussed in Maintainability Assessment, Section; that is, an average planned outage (POH) of 72 hours per year.

A power plant's reliability and availability are given by the equations

$$R_{\text{power plant}} = 1 - \frac{\text{FOH}}{8760}, \quad A_{\text{Power plant}} = 1 - \frac{(\text{FOH} + \text{POH})}{8760}$$

where FOH is forced outage hours, and POH is planned outage hours. Using these equations the Mobile Power Plant has an estimated reliability and availability of 97.2% and 96.4% respectively.

SECTION IV

SUBSYSTEM CHARACTERISTICS

This section describes the trade studies that led to the choice of the cyclic reformer for the baseline fuel processor. It also provides more detailed descriptions of the cyclic reformer and the inverter/control module.

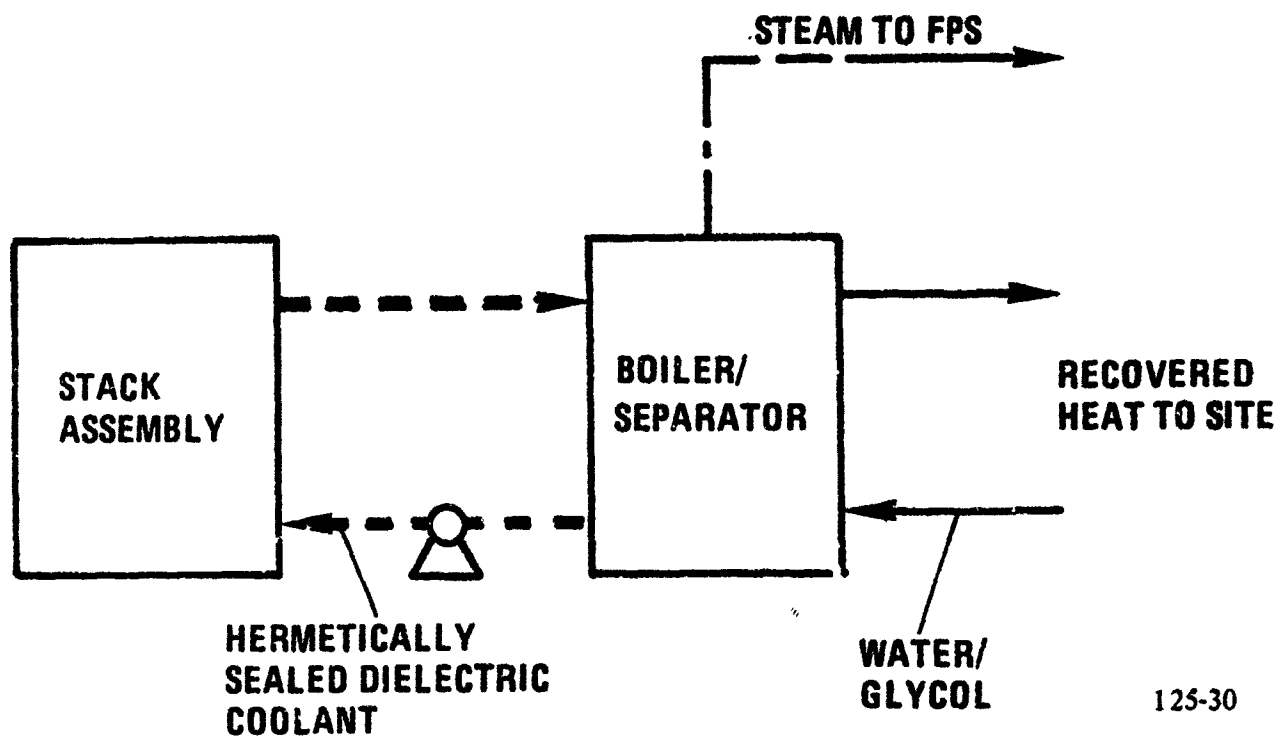
The commercial liquid cooled stacks under development are integrated into a thermal management subsystem which performs the function for raising steam for fuel processing and as required disposes of waste heat while maintaining stack operating temperature at minimum cost, and highest reliability. The full significance of liquid versus air cooling is apparent when studied in the context of combined thermal system functional requirements. Liquid cooling was selected for this commercial application after completing comparative studies which showed that for power plant larger than a few kilowatts an air cooled power plant was less efficient, heavier, and larger than a liquid cooled power plant. Specific results were:

- o Two phase liquid cooling is isothermal thus negating need for mechanical temperature controls.
- o Auxiliary power for coolant circulation would reduce overall power plant efficiency by 5 pts. or an increase of 20% in cost to provide for added auxiliary power.

Reliability of air cooling is not superior since it is more sensitive to flow maldistribution and/or local heat rejection requirements than can develop during the life of the stack. However, for the Air Force application the direct liquid cooling with water was replaced by an intermediate dielectric coolant as shown in Figure 21. This allows the stack coolant loop to be hermetically sealed similar to refrigerators and provides cold weather storage capability.

FUEL PROCESSING TRADE STUDIES

Analytical system studies were conducted to determine the preferred fuel processing concept for remote site Air Force power plants.



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Figure 21. Simplified Schematic of Stack Heat Rejection System

Commercial on-site fuel cell power plants are being developed for use with pipeline gas. This fuel is easily cleaned up and processed in a hydrodesulfurizer and catalytic steam reformer to produce hydrogen for the fuel cell. Low to moderate reformer operating temperatures enhance process heating and heat recovery, resulting in high reformer thermal efficiency. The conversion to hydrogen of heavier, high sulfur logistic fuels such as diesel fuel present a significant challenge in the development of a high efficiency fuel processor.

The requirement of high reformer operating temperatures to overcome the poisoning effects of sulfur, to prevent rapid carbon formation and achieve high fuel conversion, impose greater difficulty in providing process heat, facilitating heat recovery and achieving high thermal efficiency. Analytical studies of four logistic fuel processing systems, all of which have been experimentally evaluated by United, were conducted for the Air Force under U.S. Army contract DAAK-70-82-C-0012 to determine the optimum system to achieve high power plant efficiency with diesel fuel in a remote-site power plant. Four alternative fuel processing concepts were considered. The options included: a) thermal or high temperature steam reforming, b) adiabatic reforming, c) hybrid reforming, and d) cyclic reforming.

Operating Requirements

Three major conversion steps are involved in the reforming of logistic fuels. At moderate and high temperatures a significant portion of the fuel undergoes gasification through the homogeneous gas phase cracking of heavy hydrocarbons to light, intermediate and other products. These products include methane, ethylene propylene, naphthalene, tars, etc. As the reaction temperature is increased catalytic steam reforming, a surface reaction converts the fuel and its gasification products into oxides of carbon and hydrogen. Metallic catalysts although severely poisoned by sulfur in the fuel, attain sufficient activity at high operating temperatures to achieve high fuel conversion. The activity of non-metallic catalysts is insufficient to achieve high conversion. Therefore, the non-metallic catalyst is best suited as a "front end" zone to achieve preheating, gasification and partial reforming before the metallic catalyst final reforming zone. At high temperature steam-carbon gasification can occur, directly converting carbon to oxides of carbon

and hydrogen. This conversion step is fundamentally important in the prevention of rapid carbon formation on metallic catalysts and sets the minimum temperature at which these metallic catalysts can be employed.

As the result of numerous logistic fuel reforming programs, including those conducted for EPRI under the RP114 and 1041 programs, and the U.S. Army under DAAK-70-82-C-0012, a set of operating requirements for the fuel processor reactor have been evolved to assure high fuel conversion and carbon free operation.

- o Non-metallic gasification catalysts should be used below 1800°F. The TOYO T12 calcia-alumina non-metallic catalyst also resists the very slow build up of carbon usually experienced at moderate temperatures with heavy fuels. Continuous or frequent regeneration can be practiced with non-calcia catalysts.
- o Catalytic combustion with air and steam can be utilized to rapidly achieve temperatures above 1800°F to achieve high fuel conversion and avoid carbon formation.
- o The steam-carbon gasification reaction is sufficiently vigorous above 1800°F to allow the use of metallic catalyst without carbon formation. Below 1800°F the steam-carbon gasification rate is too slow to compete with the carbon forming reactions on metallic catalysts.
- o Once gasification is essentially complete, with the only significant remaining hydrocarbon being methane, then the catalytic steam reforming of methane can be allowed on metallic catalyst below 1800°F.

In addition there are three general fuel processing system requirements for achieving high system thermal efficiency with logistic fuels.

- o The system should provide good fuel gas quality to the fuel cell (i.e., high hydrogen partial pressure).

- o The system should maximize the use of anode exhaust energy for providing heat to the hydrogen generation process.
- o The system should maximize heat recovery from the process fuel and combustion streams.

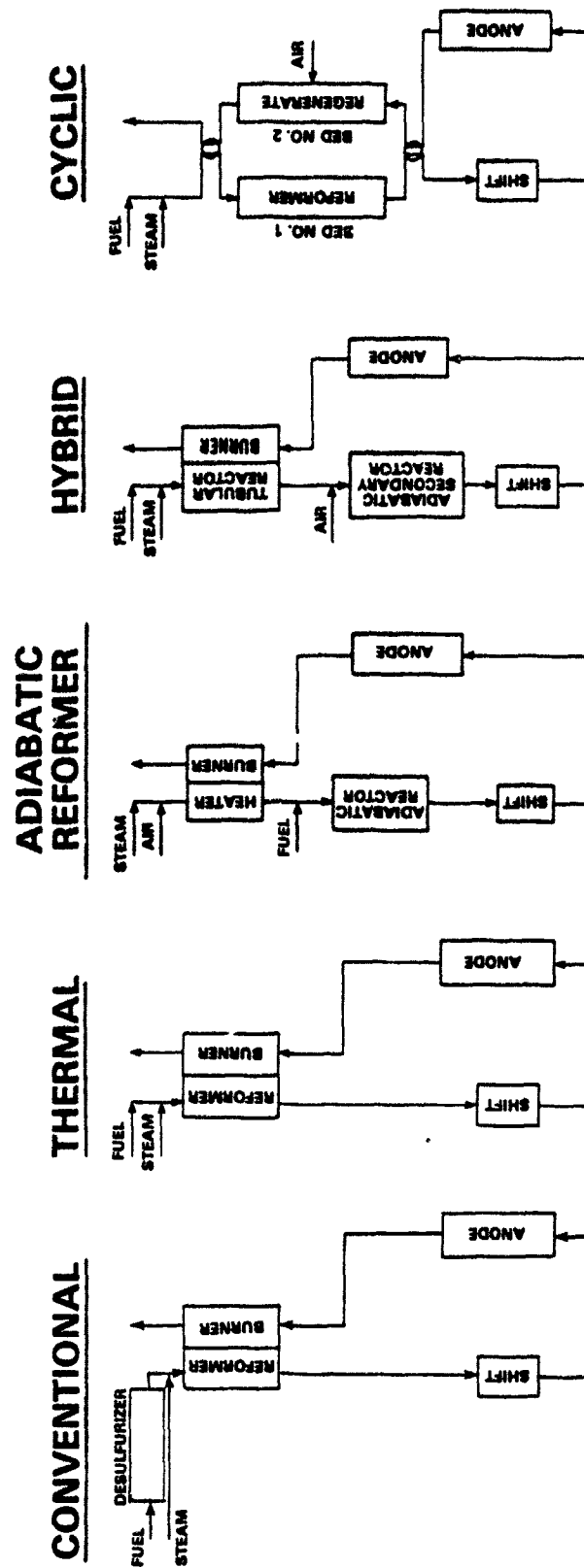
The reactor requirements for carbon free, high fuel conversion operation are not necessarily consistent with the system requirements for high efficiency. These requirements and the unique trade-offs associated with each fuel processing system formed the basis for the analytical studies, evaluations and selection described below.

FUEL PROCESSOR OPTIONS

Four alternative fuel processing concepts were considered for handling diesel fuel. A nominal power level of 100 kW was selected for this study. The requirement of remote site operating set a premium on high electrical efficiency since fuel transportation costs comprise a significant percentage of total life cycle costs. Simple sketches of these options, including the conventional steam reforming process for lighter easily desulfurized fuels, are shown in Figure 22.

Thermal Steam Reforming

This process has been studied in great detail by United in both independent and EPRI sponsored programs. Over 24 catalysts have been evaluated including the TOYO T12 and T48 total hydrocarbon reforming catalysts. Diesel fuel, containing sulfur which cannot be easily removed by conventional means in the power plant upstream of the reformer, is fed directly to the reformer. The reformer tube would



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Figure 22. Reformer Options

typically be loaded with the TOYO T12 gasification catalyst at the inlet followed by TOYO T48 nickel reforming catalyst or other suitable metallic catalyst at the hot end. Hydrogen sulfide formed in the high temperature reforming process can be conveniently removed downstream of the reformer in a zinc oxide scrubber bed. Hydrogen rich gas is fed to the fuel cell anode. Anode exhaust is burned to provide heat to the reforming process by means of indirect heat transfer from the burner gas across the walls and into the catalyst bed in the reformer tubes. Unfortunately, the requirement to maintain the T48 or other metallic reform catalyst in this system above 1800°F to achieve high conversion and carbon free operation coupled with the mode of indirect heat transfer results in excessive wall temperatures, a larger reformer size and poor reformer thermal efficiency, resulting in low power plant electrical efficiency. For these reasons, thermal or high temperature steam reforming was eliminated from further consideration.

Adiabatic Reforming

In this system fuel, preheated steam and air are fed directly to a high temperature adiabatic reactor. Adiabatic reforming has been studied extensively under EPRI, U.S. Army and United funded programs. Three major improvements which allow the adiabatic reformer to achieve high conversion carbon free operation at low oxygen to fuel ratios, resulted from these efforts. The improvements were the development of a fuel, steam, air reactant injection and mixing system, a metal oxide combustion and gasification reformer inlet catalyst, and a stable high temperature, high activity reformer exit catalyst for achieving high fuel conversion in the presence of sulfur. A schematic of a typical adiabatic reformer system is shown in Figure 23.

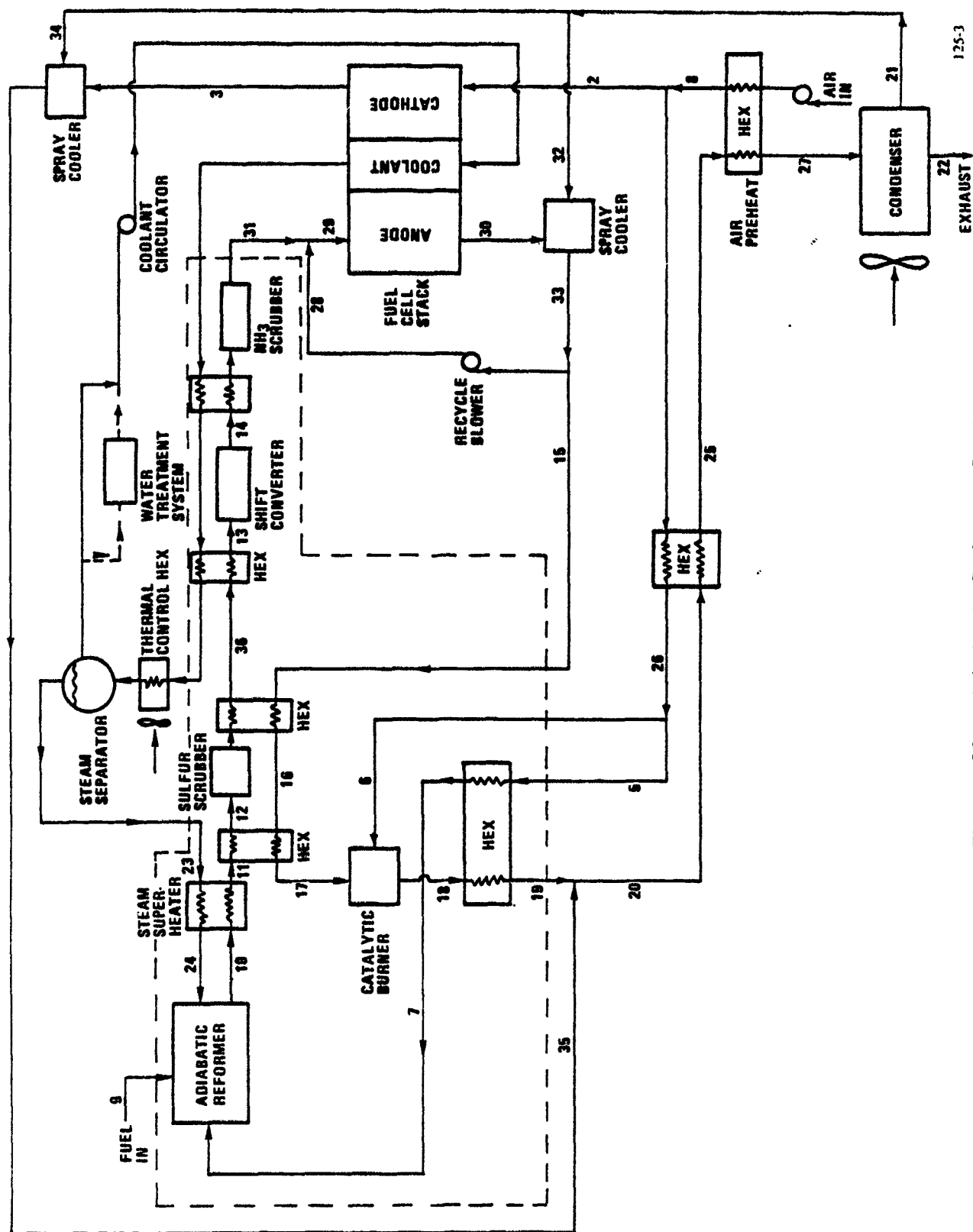


Figure 23. Adiabatic Reformer System

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The major detractor from the achievement of high efficiency in this system is the pre-combustion of fuel as a major source of direct reform process heating. This limits the theoretical yield of hydrogen available to the fuel cell and results in significant dilution of the hydrogen fuel and anode exhaust gas. This limits the hydrogen utilization in the stack and results in low power plant electrical efficiency. With an on-site stack (sized for natural gas operation at 40% electrical efficiency), a remote-site power plant with an adiabatic reformer would operate at about 30% electrical efficiency.

Hybrid Reforming

In this system a primary thermal steam reformer operating at low fuel conversion with a non-metallic gasification catalyst is used in series with a secondary adiabatic reformer. This system was studied in considerable detail for electric utility applications under the EPRI RP1041 program. A schematic of a typical hybrid system for remote-site applications is shown in Figure 24.

A significant improvement in performance over the adiabatic reformer is achieved in this system by preheating, gasifying and partially reforming at moderate temperatures (a maximum of 1750°F) the fuel-steam mixture (using anode exhaust energy for indirect heating) prior to injecting this mixture with preheated air into the secondary adiabatic reformer. The energy contribution of the primary reformer to the overall reforming process significantly reduces the amount of air required in the secondary reformer increasing fuel gas quality and cell performance. The use of a non-metallic gasification catalyst such as the TOYO T12 calcia-alumina catalyst in the primary reactor precludes the rapid formation of carbon associated with metallic catalysts operating below 1800°F. The mixer, combustion and conversion catalysts developed for the adiabatic reformer insures carbon free, high fuel conversion operation. Compared to the adiabatic reformer at 30% the predicted hybrid reformer system electrical efficiency is at least 35% with an on-site size fuel cell stack.

As in the adiabatic reformer, fuel gas leaving the reformer contains hydrogen sulfide and a small amount of ammonia formed in the reformer. These gases are scrubbed out in separate beds prior to the fuel cell.

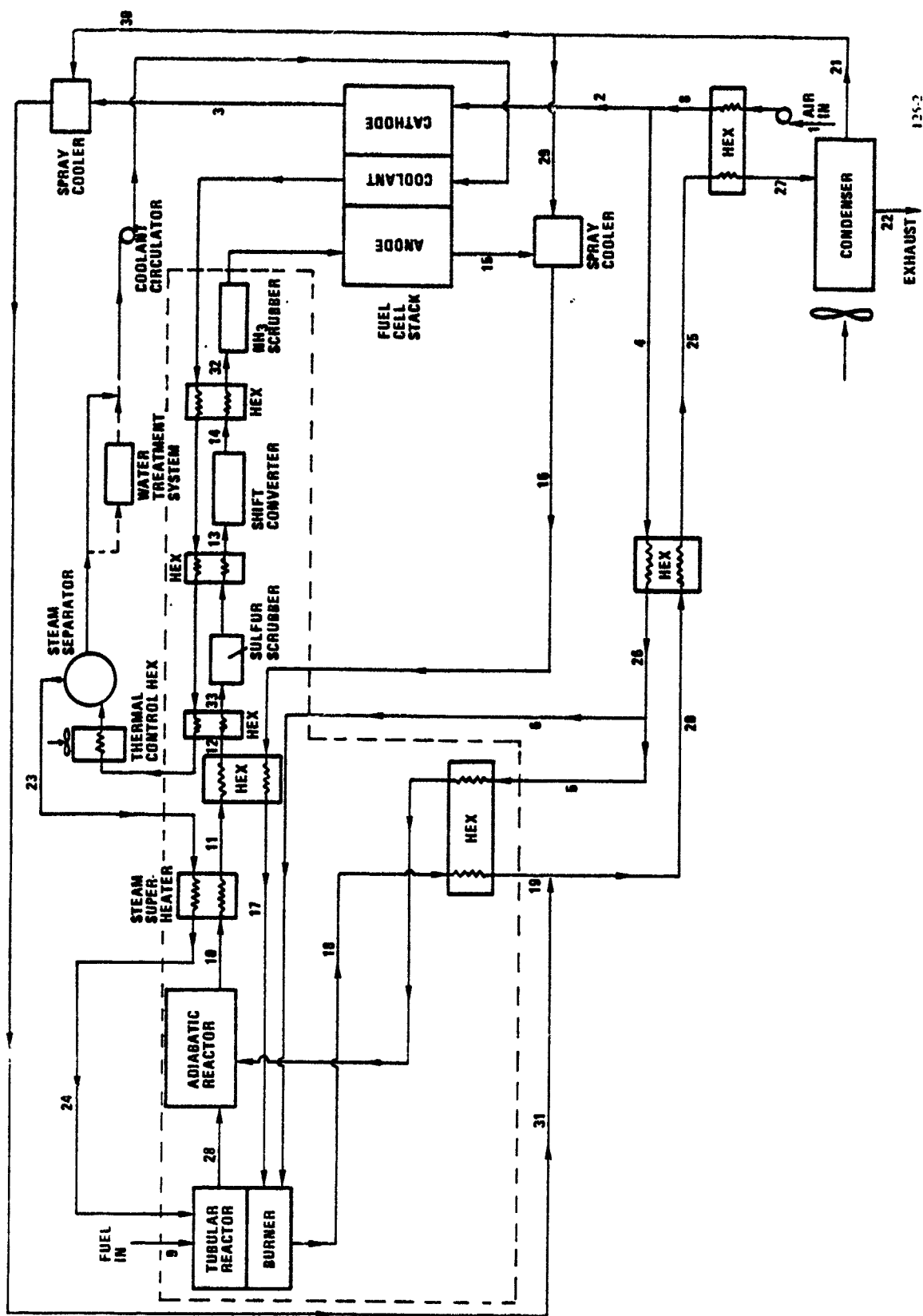


Figure 24. Hybrid Reformer System

Cyclic Reforming

This system has been studied under United sponsored programs for various utility and commercial applications. In this system two beds which store energy on heat transfer packings and catalysts are cycled every 2 to 3 minutes at rated power between a "make" and "regeneration" mode. In one bed fuel and steam are preheated, gasified and partially reformed over a ceramic non-metallic heat transfer packing and catalyst, reformed at high temperature over a metallic catalyst, and cooled and partially shifted over ceramic packing and sulfur tolerant shift catalyst. In the other bed, in a counter flow manner, anode exhaust and steam are preheated to high temperature, partially burned with air (fuel rich combustion stage) to supply heat to the metallic catalyst zone, then completely burned with air (lean combustion stage) to provide heat to the non-metallic fuel and steam preheat, gasification, and partial reforming zone.

Transition from the "make" mode of one bed to the other is accomplished in about 4 seconds using make steam purge which maintains proper volumetric flow to the stack. A hydrogen back mix plenum (placed upstream of the fuel cell stack) ensures hydrogen fuel gas quality to the stack. A schematic of a typical cyclic reformer system is shown in Figure 25.

High fuel gas quality is produced in the cyclic reformer system since no air is added to the hydrogen generation reforming process. Only anode exhaust is used to provide reform process heat. Unlike the thermal steam reformer which heats the reformer process indirectly, all heating and heat recovery is by direct contact on high surface area, high heat capacity packed beds. The predicted electrical efficiency of this system with an on-site size stack is 40%.

Since no air is used in the reform process (during make) no ammonia is formed. The cyclic reformer is also capable of scrubbing out, by the regenerative process, a significant portion of the fuel sulfur, reducing downstream zinc oxide scrubber requirements.

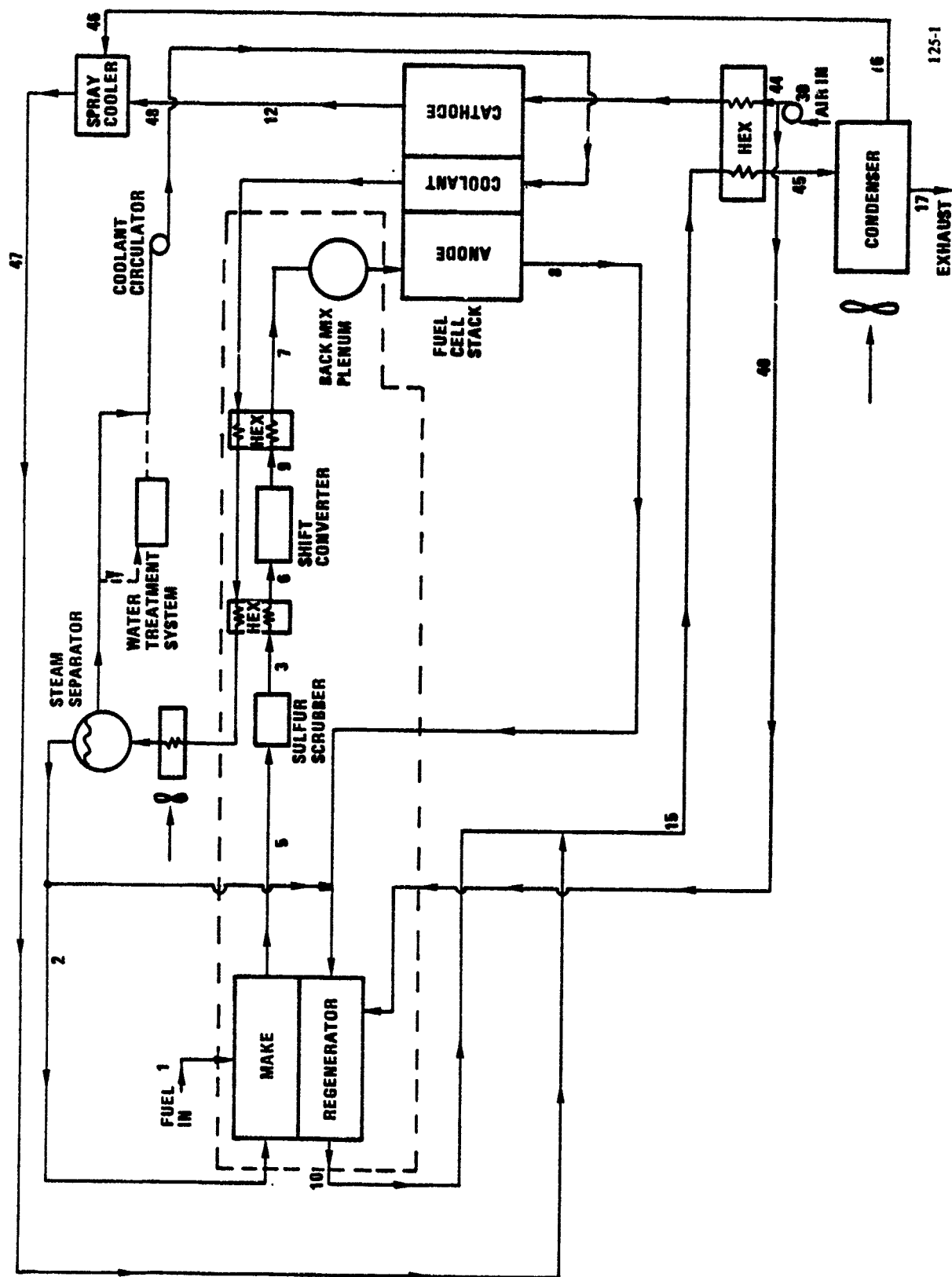


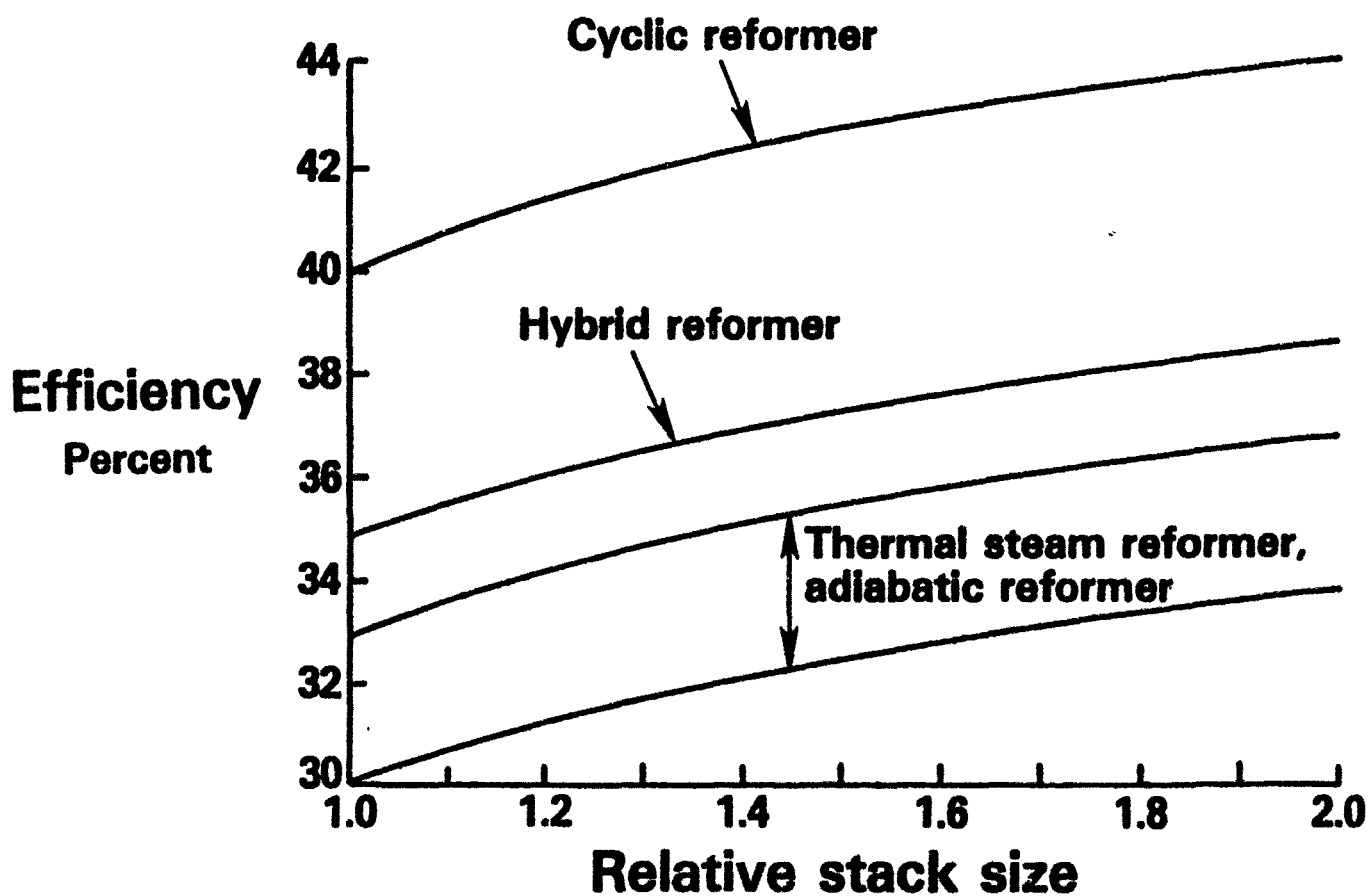
Figure 25. Typical Cyclic Reformer System

Fuel Processing System Selection

The major factor governing the selection of the fuel processor to be studied in the remote-site Air Force power plant design was power plant electrical efficiency. Figure 26 compares the predicted efficiency of all of the fuel processing system considered. Each system can be increased in electrical efficiency by increasing stack size relative to nominal on-site baseline, although the efficiency difference between the systems remains essentially constant.

The major issue concerning the selection of the most efficient process, the cyclic reformer, over the hybrid is the much higher level of development of the hybrid including its associated secondary adiabatic reformer stage. The cyclic reformer utilizes ceramics and catalyst beds which are subjected to repeated two to three minute temperature swings of up to 250°F in the hottest zones. Feed and exhaust valves, although subject to fairly moderate temperatures (in the range of 350 to 550°F) are also cycled every two to three minutes at rated power (less often at part power). It was judged that the cyclic reformer operating condition, although demanding, are probably no more severe than another proven commercial cyclic reforming processes;¹ nor is the valving actuation and frequency requirements significantly different from another reliable commercial multi-cyclic valve application². Cyclic reformer system development and reliability issues are addressed further under the component evaluation and reliability sections.

- (1) "ONIA GEGI" process for cyclic catalytic cracking of liquid hydrocarbons (production of town gas from residual fuels by a cyclic reforming and re-generation process). Soceite de Construction D'Appareils Pour Gaz a L'Eau et GAZ Industries, Montrouge (Seine) France. (See references)
- (2) Union Carbide pressure swing adsorption process plants for providing high purity hydrogen. (See references)



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Figure 26. Power Plant Efficiency vs. Relative Stack Size

Cyclic Reformer Description

Schematics of the cyclic reformer reactor subsystem and details of its individual beds are shown in Figures 27, 28, and 29. To improve packaging and start-up, the cyclic reformer gasification and reforming functions have been split into primary and final conversion beds. Two of the units shown in Figure 27 comprise a complete cyclic reformer reactor subsystem. One unit "makes" while the other unit "regenerates". Start (S), make (M), and regeneration (R) process flows and directions are designated in Figure 27.

In the make process, steam is superheated, diesel fuel is injected and vaporized, and the mixture is heated to a high temperature, where it undergoes gasification and partial reforming to oxides of carbon and hydrogen. The reform process is completed in the final conversion bed, over a metallic reform catalyst, a ceramic packing reheat zone, and a final equilibration over metallic reform catalyst. The reform products are then cooled and shifted over ceramic packing and sulfur tolerant shift catalyst. Since the shift reaction is exothermic, the extra heat recovered in the regeneration process results in increased reformer thermal efficiency. In addition, the duty and size of the downstream low temperature shift bed is reduced. Judicious placement of regenerable sulfur absorbent materials within the beds can result in the removal of significant quantities of fuel sulfur, reducing the size of the downstream sulfur scrubber, and the degree of sulfur poisoning of the reform catalyst.

During regeneration, fuel cell anode exhaust and steam are preheated utilizing stored heat on the ceramic packing and shift catalyst. A portion of the anode exhaust burns in a ceramic packing fuel rich combustion zone and then reheats the metallic reform catalyst. These fuel rich gases are then burned with excess air at the top of the primary conversion bed which reheats the ceramic packing in this bed.

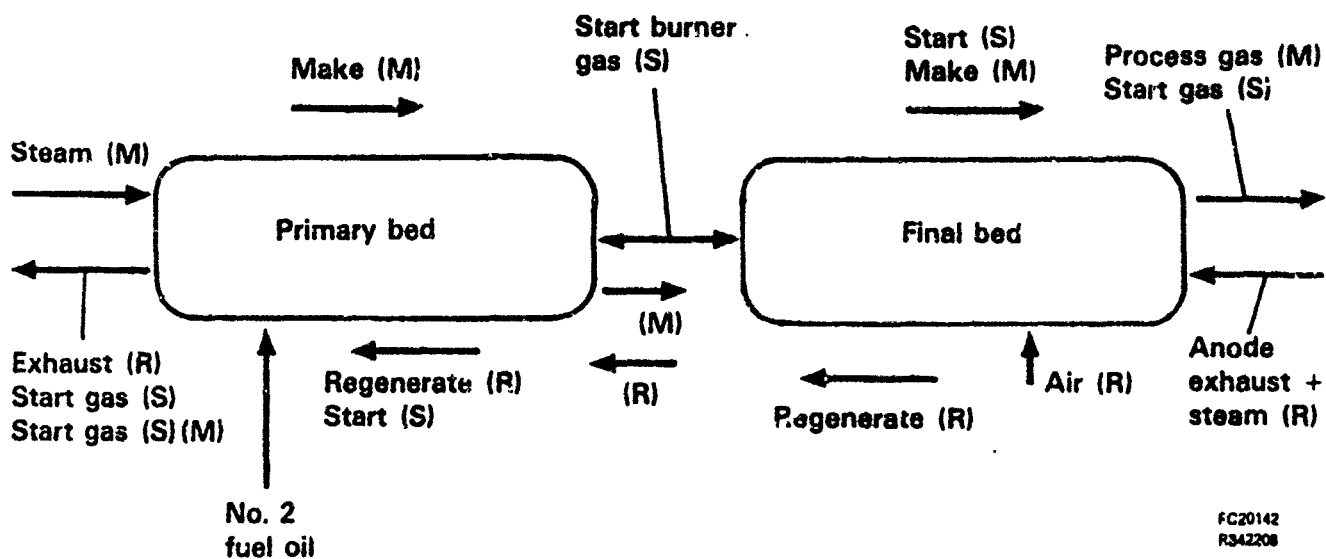


Figure 27. Cyclic Reformer - Primary and Final Conversion Bed

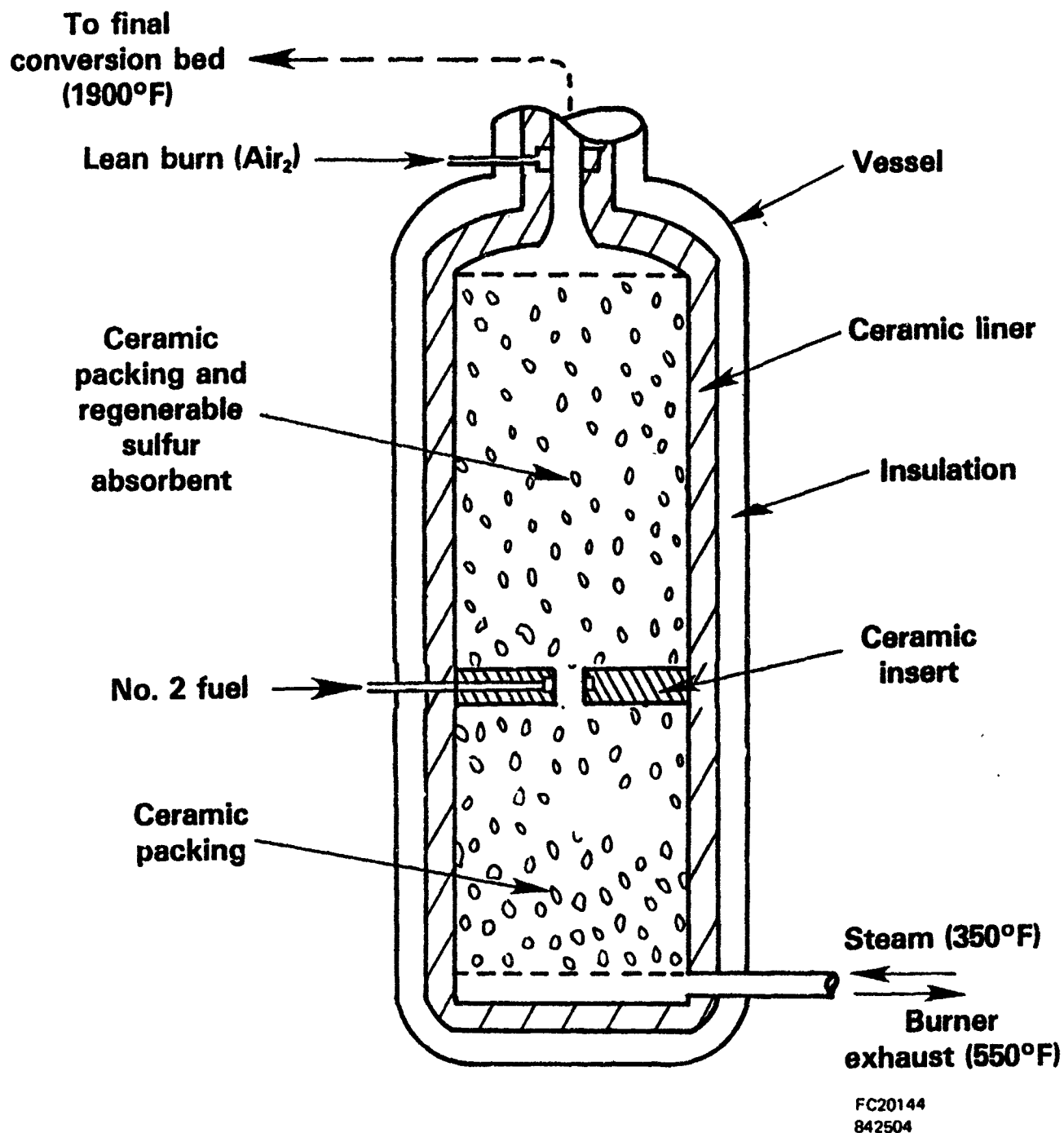
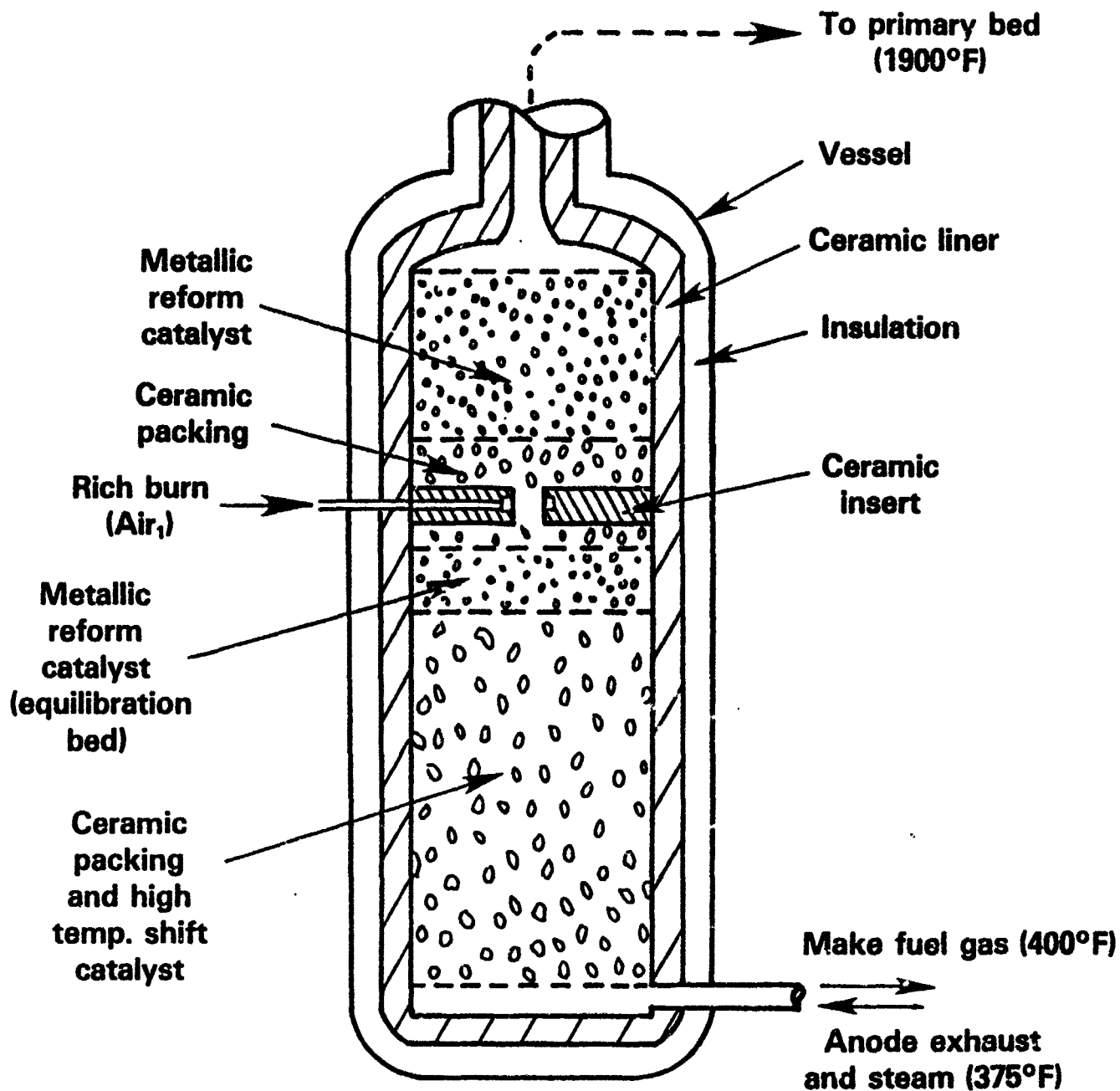


Figure 28. Cyclic Reformer - Primary Conversion Bed



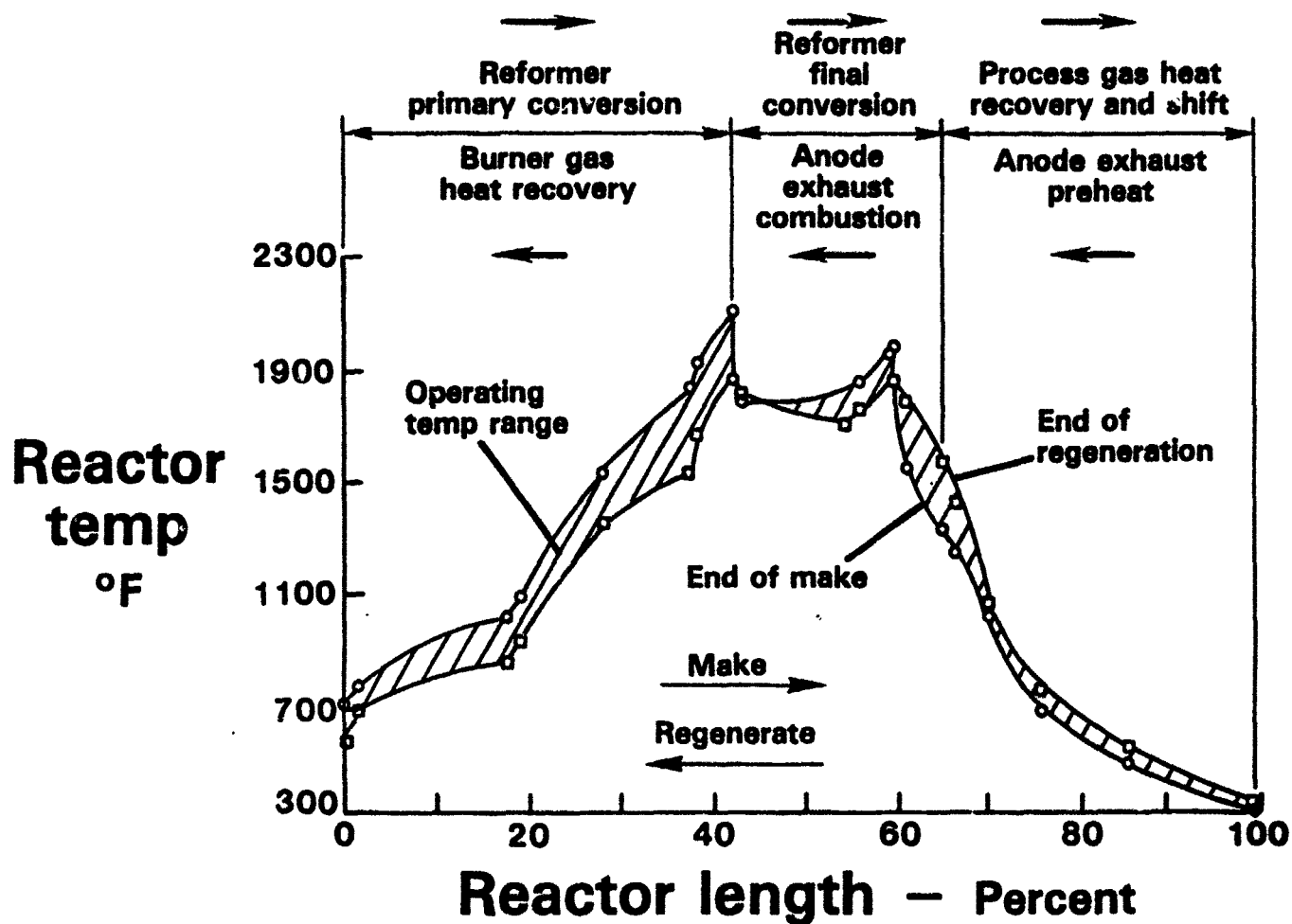
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Figure 29. Cyclic Reformer - Final Conversion Bed

Fuel rich combustion (hydrogen rich regeneration gas) in the final conversion bed minimizes the chance of metallic catalyst oxidation and reduction from cycle to cycle. Partial combustion, heat removal in the ceramic packing zone and the mixing of the metallic catalyst with ceramic packing reduces the burner gas temperature and temperature swing, minimizing cyclic stress on the reform catalyst. Lean combustion (excess O_2) in the primary conversion non-metallic catalyst bed enhances the removal of any carbon and the regeneration of sulfur absorbent materials placed in the bed. This regeneration feature overcomes many of the difficulties associated with carbon deposition associated with imperfect fuel-stream mixing.

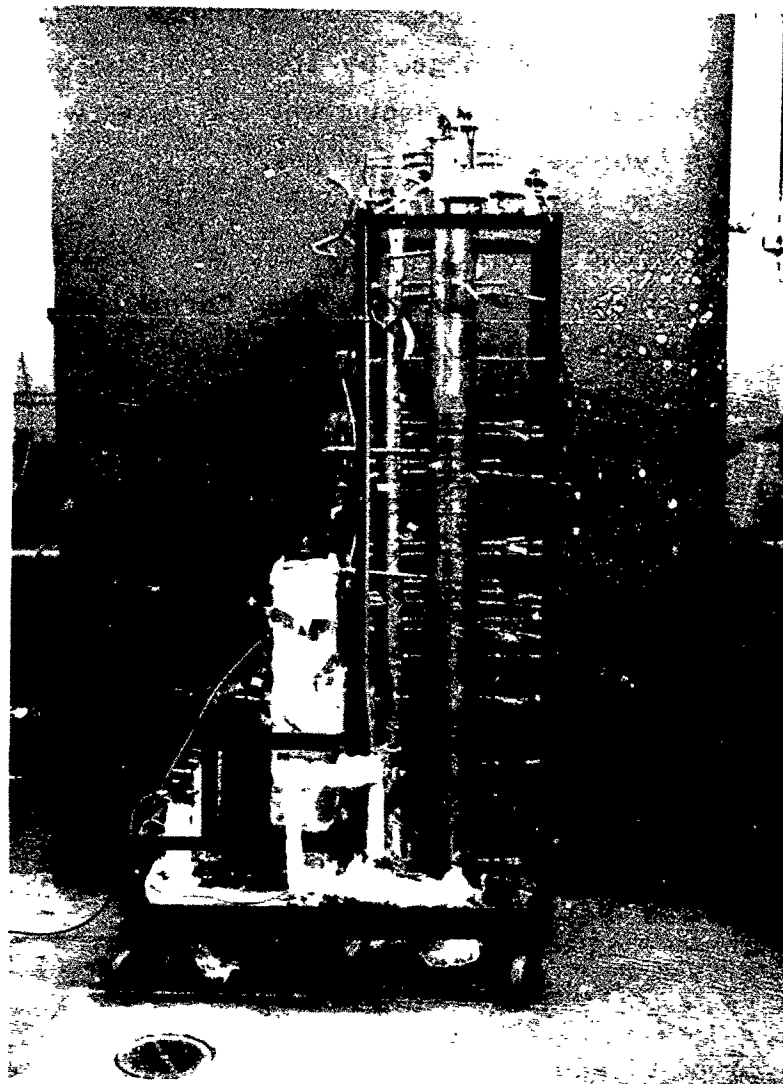
Figure 30 shows the temperature profile achieved in a UTC sponsored test of a breadboard cyclic reformer shown in Figure 31. This device was operated on naphtha fuel and with home heating oil with 3300 ppm sulfur and achieved a stable thermal profile (cycle to cycle) demonstrating the basic feasibility of the concept.

The make and regeneration cycles at rated power of the cyclic reformer is about 2 minutes each. At part power (reduced flow), cycle duration increases essentially inversely proportional to gross current. This results in a constant energy storage or temperature cycle regardless of reformer throughput. Approximately 2 seconds before the end of the make cycle on one bed (and the regeneration cycle of the other bed) the fuel is turned off and the make steam flow is increased to purge the front end of the bed of raw fuel and assure an adequate supply of hydrogen flow from the back mix plenum (H_2 tank) to the stack. At the same time air flow for regeneration is terminated allowing the anode exhaust to sweep combustion products from the bed.



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Figure 30. Cyclic Reformer Temperature Profile



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Figure 31. Cyclic Reformer Test Rig

After this 2 second period (before anode exhaust reaches the bed exhaust), the beds are switched (the regenerating bed becoming a make bed). Approximately 2 seconds into the new make cycle the make steam flow is reduced to its nominal value, and air flow is re-established to the new regenerating bed to meet the arrival of anode exhaust at the burn zones. Anode exhaust which fills the regenerating bed prior to switch over is purged by steam and fuel gas at the beginning of the make cycle into the back mix plenum where it mixes with a much larger volume of high quality, high hydrogen content fuel gas.

Most of the valves in the cyclic reformer subsystem are actuated simultaneously since steam, anode exhaust, anode supply, and burner exhaust must flow constantly. This allows these major valves to be ganged on single actuators to reduce cost and increase reliability. As described above, the fuel valves, air valves, and provision for 4 seconds of additional steam purge requires separate schedules.

Cyclic Reformer Start System

As shown in Figure 27 a start burner is used to heat the reformer beds. In order to minimize or prevent catalyst oxidation during heat up, the burner is operated at near stoichiometry. Some of the start burner exhaust gas leaving the cold ends of the beds is recycled back to the burner to provide cooling of the burner liner, enhance mixing, and lower the burner exit temperature to about 1800 to 2000°F.

Cyclic Reformer Valving System

The cyclic reforming process requires several pairs of relatively high duty cycle valves. Based on a two minute make cycle at rated power, the worst case yearly cycle rate for continuous operation would be 262,800 cycles/year. Cycle rate is reduced directly with reduced power. The selected valve for this application would be rotary, quarter-turn ball valves. The valve actuator will be double acting cylinders and will be coupled to the valves by either a scotch yoke or rack and pinion mechanism, depending on the vendor eventually selected.

Since several of the valve pairs act simultaneously, one opening as the other closes, those pairs can be ganged on a common actuator, reducing cost and improving reliability. Figure 32 shows the valve to be used in the cyclic reforming process and indicates which of these can be ganged together. The actuating medium will be instrument quality air supplied via a pilot, four-way solenoid valve. To optimize actuator life, particle size and dew point will be maintained in accordance with Instrument Society of American [ISA] standard S 7.3, Quality Standard for Instrument Air. The compressor will be $1\frac{1}{2}$ HP single stage, with a capacity of 5.5 SCFM. The majority of the compressor's capacity is required for other power-plant requirements such as the continuous air-consumption of modulating control valves. Compressor accessories will include a pressure switch to control the instrument air between 80-100 psig, as well as receiver relief valve and filter/dryer assembly.

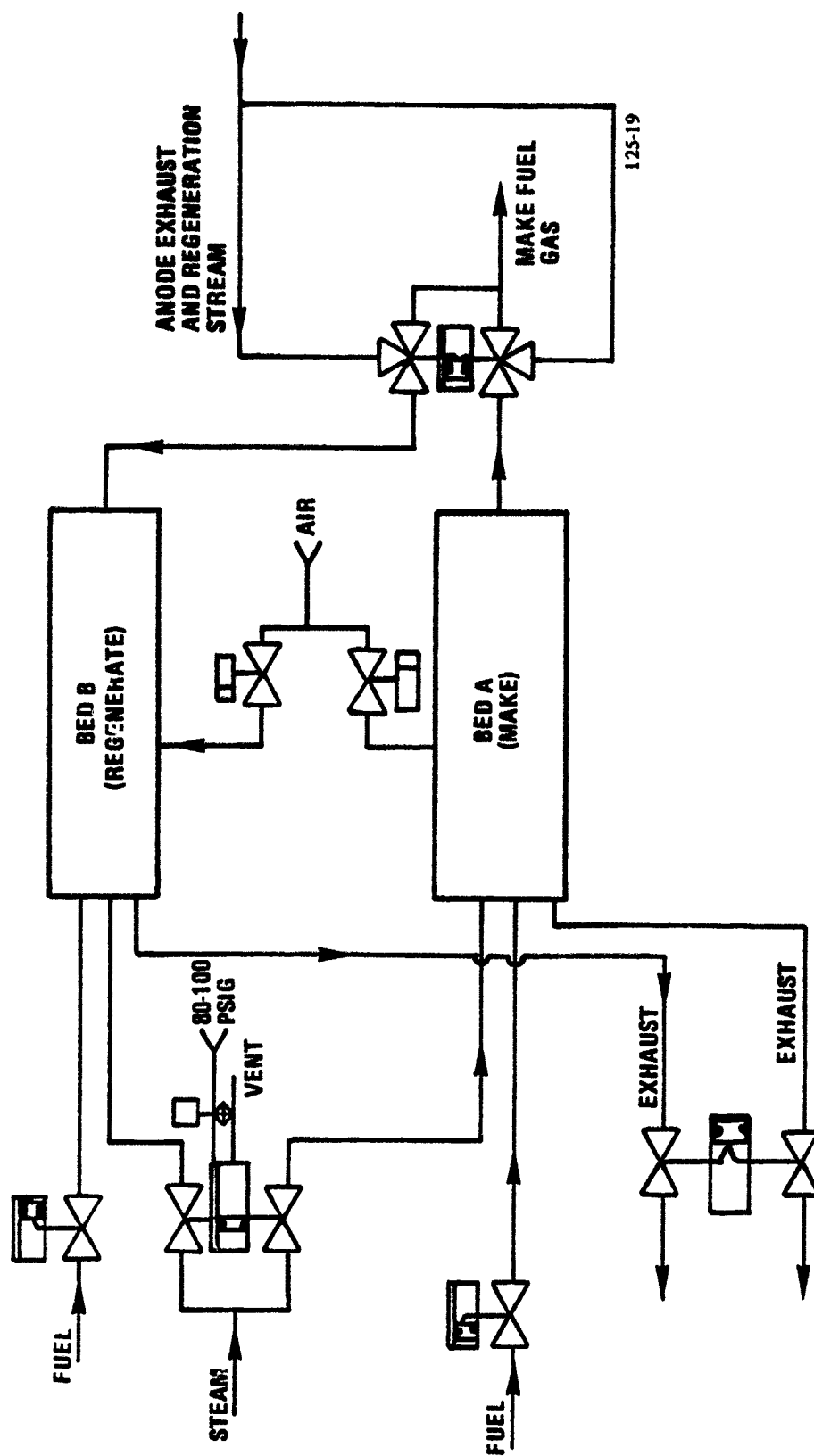


Figure 32. Valves Used in Cyclic Reforming Process

Inverter and Controls

Inverter

The inverter, which converts the fuel cell dc power to quality ac power, is an advanced design incorporating technologies identified and verified by the On-Site Program activities. The elements of the inverter, as shown in Figure 33 are a single three-phase inverter bridge, an output filter, an output transformer, and appropriate switchgear and control/protection logic.

The primary technology items required to obtain this power rating in a single compact bridge are advanced gate controlled power switching devices, advanced microprocessor logic to control the high frequency switching required for proper reduction of harmonics and dielectric cooling. The On-Site program addresses the areas of advanced gate controlled power switching devices and the use of sixteen bit microprocessors and microcontrollers for the logic; the dielectric cooling technology may be an On-Site Program derivative, or it may require specific program development.

The gate controlled power switching device is the key to this inverter design. This application being an isolated load system (not connected to the utility grid), requires switching to control the inverter generated harmonics and to provide a unit capable of supplying fault current into short circuits to clear protective branch circuit breakers. In addition, the switching devices must be capable of providing overload for transients and motor starting. This design will utilize high frequency pulse-width modulation of the switching patterns to obtain regulation of the basic 60 hertz fundamental voltage, to provide harmonic voltage control, and to provide a current-limited amount of fault current. The advanced gate controlled devices will be selected based on their ability to provide about 1.8 times continuous rating for five second overloads such as motor starting. The overall device load plus overload requirements, along with the need for a compact mechanical design dictate the need for dielectric cooling.

The basic items shown in Figure 33 are described as follows:

- o The inverter bridge is a three-phase bridge utilizing gate controlled power switching devices. The gate controlled devices can be turned on and off by proper gate signals and do not require energy storage communication circuits for turn-off. The devices have very rapid turn-on (< 1 microsecond and turn off (< 5 microseconds) times which allow the high frequency of switching required for harmonic voltage control. The switching control is utilized to place the bridge generated harmonic voltages at frequencies where filtering is performed more easily. To provide for a compact physical package, the devices are dielectric (liquid) cooled which allows more heat to be conducted from a given device area than more conventional means such as forced air with fin type heatsinks.
- o The series reactor and filter provide two basic functions. (1) The series reactors (an inductor in series with each of the bridge three-phase outputs) provide a known inductance in each output line which establishes a defined maximum rate of current rise (di/dt) and thus the required switching control for operation into load short circuits can be determined (2) The filter, in conjunction with the series reactors, can be tuned to trap (shunt) harmonics that are generated. Proper waveform pulse-width-modulation control will place undesired harmonics at frequencies where the filter requirements are minimized in regards to kVA rating.
- o The output transformer also provides two basic functions. (1) It steps up the inverter bridge output voltage to a level that is appropriate for the load system. The inverter output characteristics are shown in Table 10. (2) The transformer provides isolation between the fuel cell/inverter and the load and allows grounding of the secondary neutral to provide a three-phase four-wire power feed to the load with the fourth wire grounded (it can be ungrounded if desired).

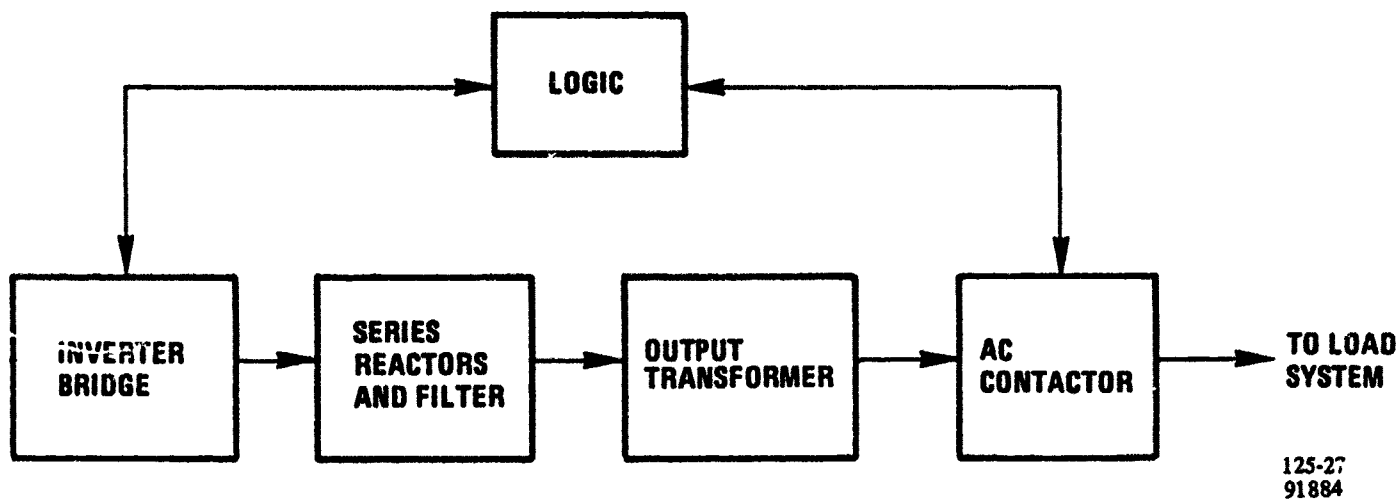


Figure 33. Inverter System Schematic Diagram

Table 10. Power Plant Electrical Output Characteristics - 100 kW

	<u>FUEL CELL</u>	<u>IGLOO DIESEL</u>
VOLTAGE FREQUENCY	120/208/60 Hz	120,208/60 Hz
STEADY STATE STABILITY	Voltage - 1% Frequency - 0.0002%	
TRANSIENT PERFORMANCE:		
Frequency	0.0002%	
Voltage	±5% (2-4 Cycles)	5% (3 Secs.)
Apply Rated Load	-5% (2-4 Cycles)	
Removed Rated Load	+5% (2-4 Cycles)	
Motor Load	5%	
Overload	180 KVA/0.7 P.F.	110% (2 Hrs.)
WAVE FORM:		
Max. Dev. Factor	5%	5%
Individual Harmonics	3%	3%
REGULATION:	Voltage ±5% Frequency - 0.0002%	

- o The ac contactor provides functions for automatic startup and load connect and automatic shutdown and load disconnect.
- o The logic utilizes advanced microprocessors for control and protection of the inverter. Completely automatic start and stop and response to load demand are provided, as well as current limit action to provide operation during load fault conditions. The logic contains self checking diagnostics as well as indicators to show reason(s) for any shutdowns. This inverter logic will be integral with the logic utilized to control the fuel cell and fuel processing portions of the fuel cell power plant system. The logic is interfaced to the inverter power structure (bridges, ac contactor) via fiber optics to provide communications lines that are effectively insulated from high voltage and isolated from any electrical noise that could cause improper operation. The logic also allows paralleling of multiple units with accurate load sharing.

Table 11 summarizes the inverter features.

Table 11. Inverter Features

Number of 3 phase bridges	One
Power semiconductors	Gate controlled (no commutation circuitry)
Voltage/harmonic control	Pulse-width modulated
Logic	Microprocessor
Efficiency	>93%
Communications lines	Fiber optics
Technology advances	Gate controlled semi-conductors dielectric cooling

Controls

The inverter and dc module are controlled and protected via an integral advanced microprocessor based subsystem. The design makes maximum use of off-the-shelf microcomputer hardware with screening and burn-in to enhance reliability and is structured to minimize interface hardware requirements such as sensors or solenoids by optimizing the software capability of the microprocessors. The logic incorporates self-checking and diagnostics functions to simplify identification of any problems that occur. Susceptibility to noise is absolutely minimized by use of multiplexed fiber optic communications links, which along with the microprocessors, constitute the key technologies. The system EMI/RFI capability is defined in Table 12. The On-Site program development activity will verify the ability of fiber optic communication lines for eliminating any EMI/RFI interference problems. Table 13 depicts the features of the controller logic, which also apply to the inverter logic.

TABLE 12. Environmental/Logistical - EMI/RFI Capability

- o CONTROLLED BY COMMERCIAL DESIGN PRACTICES TO MINIMIZE GENERATION/SUSCEPTIBILITY INCLUDES
 - IEEE STD. 518-1977,
 - FCC 79-555, 14686 TECH. STD. FOR COMPUTING EQUIPMENT,
 - FCC REQUIREMENT FOR INCIDENTAL OR INDUSTRIAL CLASS RADIATOR, AND
 - DESIGNS INTENDED TO MEET MIL-STD-461B
-

Table 13. Power Plant Controller and Inverter Logic Features

-
- o ADVANCED MICROPROCESSOR TECHNOLOGY
 - SELF CHECKING
 - DIAGNOSTICS
 - o FIBER OPTICS COMMUNICATIONS
 - o SOFTWARE FLEXIBILITY
 - o COMMERCIAL OFF THE SHELF MICROS FOR PROVEN RELIABILITY
 - o EMI/RFI SHIELDED/PROTECTED
 - o MINIMAL USE OF ANALOG CIRCUITRY
-

The control subsystem also contains an uninterruptible power source to maintain power plant control functions for situations such as faults in the load system which can significantly perturbate the load ac bus voltage. The power plant motor control center and wiring distribution box are carried as part of this subsystem.

Mechanical Design

The inverter, controls and power plant electrical distribution box are combined into an Electrical Module as shown in block diagram for in Figure 34 and as a conceptual package in Figure 4-15. The Electrical Module has a volume of 100 ft³ and an estimated weight of 1800 pounds.

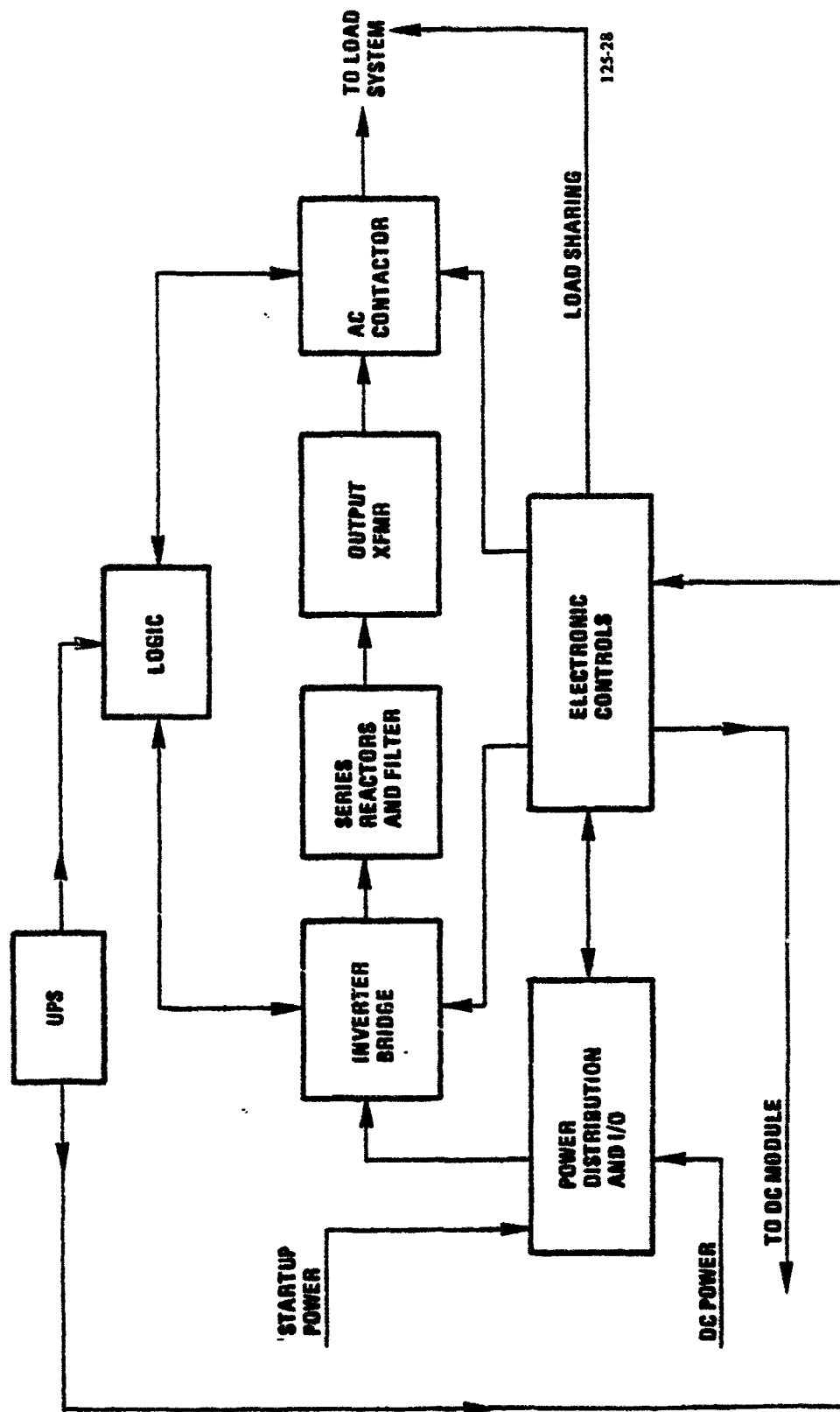


Figure 34. Electrical Module Block Diagram

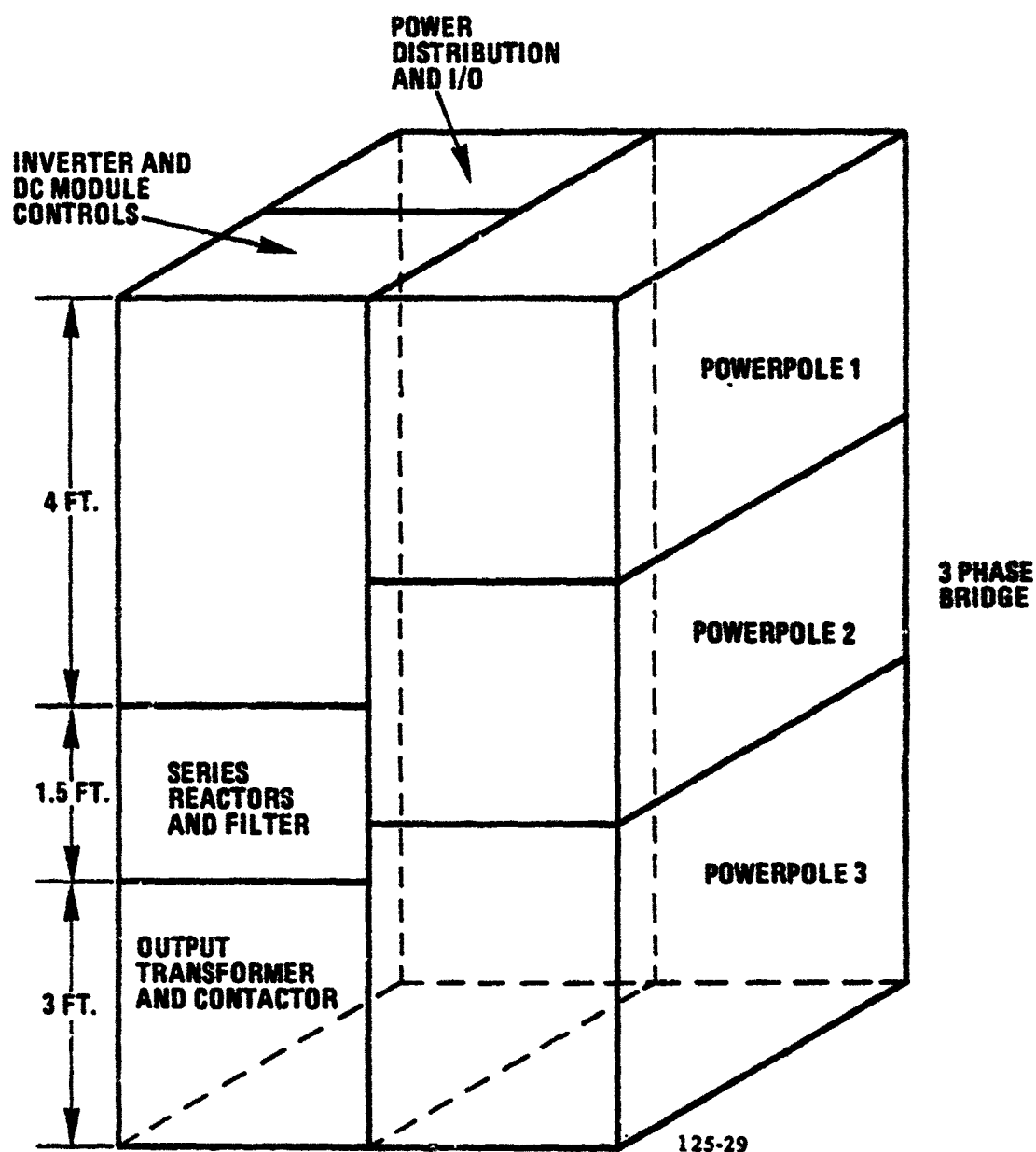


Figure 35. Air Force Power Plant Electrical Module Configuration

Table 14. Inverter/Controller Program Requirements

-
- o ESTABLISH GATE CONTROLLED SEMICONDUCTOR AND DIELECTRIC COOLING TECHNOLOGY
 - o INTEGRATE TECHNOLOGY ADVANCEMENTS INTO COMPACT PACKAGING DESIGN
 - o DESIGN/DEVELOP INVERTER/CONTROLLER
 - o COMPLETE DESIGN DEFINITION
 - o QUALIFY INVERTER/CONTROLLER SUBSYSTEM
-

COMPONENT EVALUATION

It is intended that the Air Force fuel cell power plants described in the previous sections be direct derivatives of United On-Site power plant program, and use technology, components and parts developed for this commercial power plant wherever possible. This philosophy will minimize both non-recurring and recurring cost for the power plant. The major on-site commercial components shown on Drawing FC7660 were listed and each was evaluated relative to the Air Force Power Plant requirements to determine status and deficiencies against their technical requirements. This analysis is presented in the Appendix. Also included are the new and modified components required for the cyclic reformer fuel processing subsystem.

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1. "ONIA GEGI" Process for Cyclic Catalytic Cracking of Liquid Hydrocarbons, London Gas Journal, April 3, 1957 and A.G.A. Operation Section Conference Paper 1958, by Gordon L. Calderwood, Rochester Gas and Electric Corp., Rochester, NY.
2. "PSA Produces Low-Cost, High-Purity H₂", Hydrocarbon Processing, March 1979, and "PSA Hydrogen Plants - How Well Have They Performed", Union Carbide Corporation Publication, Union Carbide Corporation, 270 Park Avenue, New York, NY 10017.

APPENDIX

POWER PLANT PROCESS COMPONENT EVALUATION

POWER PLANT PROCESS COMPONENT EVALUATION

<u>Component Name</u>	<u>Application Requirements</u>	<u>Qualification Status</u>	<u>Deficiencies</u>
Cyclic Reformer Fuel Process Subsystem	Provide Continuous Hydrogen Supply to Fuel Cell	Single bed operation demonstrated. Transient analysis (system volume dynamics) of dual bed cyclic reformer system made for electric utility power plant.	Transient flow thermal, and kinetic analysis of cyclic reformer bed and fuel processing subsystem required. Demonstration of operation of complete reformer and valving subsystem required.
Cyclic Reformers Burners, Ceramic Packing, Vessel Liner and Insulating Materials	Used as materials of construction, provide energy storage, and heat transfer function.	Materials used in constant operating temperature, high temperature secondary reformers for commercial hydrogen production.	Demonstration of long term material mechanical stability during thermal cycling required.
Cyclic Reformer Catalysts	Convert fuel and steam hydrogen.	Stability of high temperature catalysts demonstrated with high sulfur logistic fuels at constant temperature and composition (gas) conditions.	Demonstration of long term catalyst stability (high conversion) under high sulfur cyclic temperature and composition conditions required.
Regenerable Sulfur Absorber	Remove fuel sulfur. Enhance operation of catalysts and reduce zinc oxide bed requirements.	Regenerable scrubber materials demonstrated under EPRI RP114 program.	Demonstration long term carbon free operation required. Demonstration of sulfur removal materials under cyclic conditions required.
Start Burner System	Heat beds to operating temperature without severely oxidizing catalysts.	Similar to inert gas generator combustor system.	Demonstration of soot free operation at near stoichiometric conditions required. Demonstrate start system.

POWER PLANT PROCESS COMPONENT EVALUATION

POWER SECTION

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
Fuel Cell Power Section CSA	<p>100 kW equivalent output rating</p> <p>-65°F storage</p> <p>Compatible with Military Air transportation physical requirements.</p>	<p>Applicable power section including intercell cooler elements designs are being defined by the on-going On-site development program.</p> <p>The power section design development will have a basis:</p> <ul style="list-style-type: none"> o 40-kW power plant field test program (50 units) o 4.8 MW TEPCO power plant installation in Japan. 	<p>Cooling system material selections and packaging design requirements for a freeze tolerant power section.</p> <p>Verification of 2 phase hermetically sealed dielectric systems with steam separator and start burner.</p>

POWER PLANT PROCESS COMPONENT EVALUATION

BURNER SPACE

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
THERMAL MANAGEMENT START BURNER BRN-302	Q = 260,000 Btu/hr Purpose: Power section thermal control and heat integrated with HX 302 in water water/glycol loop.	Commercial burner designs are used in Electric Utility power plants. PC19 power plant testing verified the design process.	Verify design changes required for fuel conversion from naphtha to Dfa diesel fuel.

POWER PLANT PROCESS COMPONENT EVALUATION

WATER TREATMENT SYSTEM

<u>COMPONENT</u>	<u>REQUIREMENTS</u>	<u>QUALIFICATION STATUS</u>	<u>DEFICIENCIES</u>
FEEDWATER FILTER FIL 400 A, B	224 PPH H2O @ 107°F and 32.8 psia Remove dissolved impurities from feedwater and produce boiler quality feedwater.	Commercially available com- ponents Exchange type tanks con- taining resins for removal of cationic, anionic and organic contaminants. Examples: o Aqua Media o Model BC-577 o Activated carbon (organic removal) 2 ft. ³ vessel o Aqua Media o Model MB200 Vessel o "Diatond Shamrock" resin P/N ARM 381 (mixed bed demineralizer)	None
FEEDWATER DEMINERALIZER DMN 400	224 PPH H2O @ 107°F and 32.8 psia Remove suspended impurities from feedwater; 5u and larger.	Commercially Available Example: AMF-CUNO Filter Assy P/N - 44153-02 Housing 5u elements Acrylic fiber with phenolic resin	None

POWER PLANT PROCESS COMPONENT EVALUATION
WATER TREATMENT SYSTEM (Cont'd)

<u>COMPONENT</u>	<u>REQUIREMENTS</u>	<u>QUALIFICATION STATUS</u>	<u>DEFICIENCIES</u>
FCV 406 Boiler Blowdown Valve and Control	Auto blowdown to drain. 5 to 10% of throughput steam rate.	Commercial components available Example: o Blowdown solenoid valve o "Skinner Precision Co." o P/N V5H70440 Auto-control to be integrated with general power plant control system and software.	None
WATER TANK TNK 400	Water Storage vessel quantity? Degasification reduction of dissolved CO2 to 5 ppm by continuous air bubbling at 5 CFM	Vessel 40 kW On-Site design derivative: geometry to meet power plant water storage re- quirements. Material - compatible with condensate water chemistry - (300 SST example)	None

POWER PLANT PROCESS COMPONENT EVALUATION

HEAT EXCHANGER

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
BOILER SEP 402	<p>Q = 392,789 Btu/Hr</p> <p><u>Hot Side</u></p> <p>Dielectric coolant</p> <p>Temp - 370°F (inlet)</p> <p>Flow - 12,500 PPH</p> <p>Delta P - 42 lwg</p> <p>Glycol/water</p> <p>Temp - 200°F (inlet)</p> <p>Flow - 6,514 PPH</p> <p>Delta P - 28 lwg</p> <p><u>Cold Side</u></p> <p>Water</p> <p>Temp - 330°F (outlet)</p> <p>Flow - 349 PPH</p> <p>Delta P - 28 lwg</p> <p>Press. - 26 PSIA</p>	<p>Commercial shell and tube boilers are available</p> <p>Candidate vendors are:</p> <ol style="list-style-type: none"> 1. Ametech 2. Bosco 3. American Standard 	None
ACID CONDENSER HE-302A	<p>Q = 42,877 Btu/Hr</p> <p><u>Hot Side</u></p> <p>Fluid - cathode exhaust</p> <p>Flow - 1040.6 PPH</p> <p>Temp - 400°F (inlet)</p> <p>Delta P - 0.4 lwg</p> <p><u>Cold Side</u></p> <p>Flow - Glycol/water</p> <p>Flow - 6514 PPH</p> <p>Temp - 200°F (outlet)</p> <p>Delta P - 28 lwg</p>	<p>Commercially available unit using Teflon coated copper tube</p> <p>Possible candidate vendors:</p> <p>Condensing Heat Exchanger Corp.</p> <p>Verified acid compatible materials with shell and tube heat exchanger by rig testing</p>	None

POWER PLANT PROCESS COMPONENT EVALUATION
HEAT EXCHANGER (Cont'd)

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
WATER CONDENSER HE-302B	<p>Q = 455,453 Btu/Hr</p> <p><u>Hot Side</u></p> <p>Fluid - Regeneration Exhaust Flow - 1604.8 PPH Temp - 363°F (inlet) Delta P - 0.8 iwg</p> <p><u>Cold Side</u></p> <p>Fluid - Glycol/water Flow - 6514 PPH Temp - 192°F (outlet) Delta P - 28 iwg</p>	<p>Commercial coil assemblies for this application are available</p> <p>Candidate vendors are: 1. Rigdbilt Inc. 2. Anderson-Snow Corp.</p>	None
HI AND LO GRADE HEXS HE-402A and B	<p>Q = 443,035 Btu/Hr</p> <p><u>Hot Side</u></p> <p>Fluid - Glycol/Water Flow - 6514 PPH Temp - 190°F (inlet)</p> <p><u>Cold Side</u></p> <p>(Determined by customer requirements)</p>	<p>Commercially available shell and tube units</p> <p>Typical vendors are: 1. Ametek 2. Basco 3. American Standard</p>	None

POWER PLANT PROCESS COMPONENT EVALUATION

PROCESS CONTROL COMPONENTS

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
FCV 200A Fuel Control Valve Badger - Meter Research Valve Assy 316 SST Body Trim K, equal Percentage Trim ATO Position Type BLRA per 3-15 psig Signal	W = 48.7 lb/hr P = 50 psig P = 38 psig T = 95°F SG = .95 CV = .015	(1) Standard commercial hardware used on PC-19, 4.8-MW power plants (2) Compatible with ANSI B31.1 piping	
Process Fuel Shutoff (Cycle Valves)			
FCV 200B FCV 200C Jamesbury 1/4" Ball Valve B2236TT with SI50 Actuator	W = 48.7 lb/hr Pin = 7.5 psig 50 psig max. T = 95°F max. Process Fuel Service	(1) Utilized on PC19, 4.8 MW power plants (2) Qualified to API 607 (fire test for soft seated valves) and NACE Specification MR01-75 (3) USCC category "A" valve (4) High cycle line demonstrated on Union Carbide "Pressure Swing Absorption" skids	Design verification of equipment life and mean time between failure goals

POWER PLANT PROCESS COMPONENT EVALUATION
PROCESS CONTROL COMPONENTS

<u>COMPONENT NAME</u>	<u>APPLICATION REQUIREMENTS</u>	<u>QUALIFICATION STATUS</u>	<u>DEFICIENCIES</u>
<u>Process Steam Shutoff (3) Valves</u>			
FCV 404A Jamesbury 1" B236MT with ST30 Actuator	Steam Service W = 225 lb/hr P in = 23 psia T = 330°F	1) Utilized on PCI9, 4.8 MW power plant 2) High "cycle life" demonstrated on Union Carbide "pressure swing absorption skids. Air filtration required. 3) Rate to 250 psig saturated steam service. 4) Rated for ANSI B31.1 piping	Verification of design goals for operating life and mean time between failure goals
FCV 204, 206, 207 FPS Burner Shutoff Valve ASCO Solenoid Valve	FPS Start Fuel P = 50 psig T = 95°F max. W = TBD	Standard industrial U/L listed solenoid valve assy	None
FCV 203 TMS Burner Fuel S/O Valve ASCO Solenoid Valve	TMS Start fuel P = 50 psig T = 95°F max. W = 1.5 GPM	Standard industrial U/L listed solenoid valve assy	None

POWER PLANT PROCESS COMPONENT EVALUATION
PROCESS CONTROL COMPONENTS

<u>COMPONENT NAME</u>	<u>APPLICATION REQUIREMENTS</u>	<u>QUALIFICATION STATUS</u>	<u>DEFICIENCIES</u>
FCV 405 Steam Purge (ASCO Solenoid Valve) 8222A68	W = TBD P = 20 psia T = 330°F	Standard industrial UL listed solenoid valve assy	None
FCV 203 Fuel Purge Solenoid Valve Jamesbury 1/4 82236MT Ball Valve with ST50 Pneumatic Actuator	W = TBD P = 15.4 psia T = 400°F	(1) Utilized on PC-19, 4.8-MW power plants (2) Suitable for ANSI B31.1 piping	None
FCV 302 A and B Burner Exhaust Air to Start Burner Jamesbury 2" 82236MT Ball Valve with ST200 Pneumatic Actuator	W = TBD P = 15 psia T = 400°F	(1) Utilized on PC-19, 4.8-MW power plants (2) Suitable for ANSI B31.1 piping	None

POWER PLANT PROCESS COMPONENT EVALUATION
PROCESS CONTROL COMPONENTS

<u>COMPONENT NAME</u>	<u>APPLICATION REQUIREMENTS</u>	<u>QUALIFICATION STATUS</u>	<u>DEFICIENCIES</u>
FCV 404 Modulating Steam Flow Control Valve 3/4" NPT BA2236MT with B605 Actuator Type 3200 Positioner and Type PT Positioner X-mitter	W = 225 lb/hr Pin = 27.9 psia T = 330°F CV = 8.06	1) Utilized on PC19 4.8-MW power plant 2) Suitable for ANSI B31.1 piping	
<u>Reformer Air Shutoff Cycle Valves</u> FCV 102A FCV 102B Jamesbury 1" .2236 MT with ST 50 double acting cylinder	Air Service P = 14.89 psia T = 320°F W = 308.3 lb/hr	1) Utilized on PC19, 4.8 MW power plant 2) High cycle life demonstrated on Union Carbide pressure swing absorption skids 3) Suitable for ANSI B31.1 piping	Maintenance cycle verification for developed design
<u>Reformer Process Fuel Make/Regenerate (Cycle) Valves</u> FCV 201A FCV 201B 2" AN150FD 2236 MT with ST 200 actuator	Process fuel service P = 7.5 psig T = 400°F W = 292 lb/hr	1) Utilized on PC19, 4.8 MW power plant 2) High cycle line demonstrated on Union Carbide pressure swing absorption skids 3) Suitable for ANSI B31.1 piping	Maintenance cycle verification for developed design.

POWER PLANT PROCESS COMPONENT EVALUATION

PROCESS CONTROL COMPONENTS

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
FCV 104 TMS Start Air ASCO	P = 15.696 psia T = 95°F W = TBD	Standard industrial U/L listed solenoid operated valve	None
FCV 103 TMS Burner Start Air ASCO Solenoid Valve	P = 15.696 T = 95°F W = TBD	Standard industrial U/L listed solenoid operated valve	None
FCV 101 Cam Air Control Valve 3" Jamesbury Butterfly Valve 3-815W-2236TT with C60S Actuator and Type 3700 Positioner	W = 1025 lb/hr T = 95°F max. Pin = 15.696 psia P Avail. = 30 psi Valve CV = 103	1) Standard commercial hardware utilized on PC-19, 4.8-MW power plant 2) ASCO approved for category "A" service	None

POWER PLANT PROCESS COMPONENT EVALUATION
PROCESS CONTROL COMPONENTS (Cont'd)

<u>COMPONENT NAME</u>	<u>APPLICATION REQUIREMENTS</u>	<u>QUALIFICATION STATUS</u>	<u>DEFICIENCIES</u>
FCV 105 A and B Start Burner Air (ASCO Solenoid Valve)	P = 15.696 T = 95°F max. W = TBD	Standard industrial U/L listed solenoid valve assy	None
<u>Reformer Burner Exhaust (Cycle) Valves</u>			
FCV 302A FCV 302B 2" B2236 MT with ST 60 actuator	Burner Exhaust Service P = 14.9 psia T = 545°F W = 565 lb/h	1) Utilized on PC19, 4.8 MW power plants 2) High cycle life demonstrated on Union Carbide "Pressure Swing Absorption" skids 3) Air filtration required 4) Suitable for ANSI B3.1 piping	Verify valve design for life and mean time between failure objectives
<u>Reformer Air Control Valve</u> FCV 102 A and B	W = 88 lb/hr T = 95°F max. Pin = 15.696 psia P = .693 psia Valve CV = 6.3	1) Utilized on PC-19, 4.8-MW power plants 2) Suitable for ANSI B31.1 piping 3) USC6 approved for Category A service	None

POWER PLANT PROCESS COMPONENT EVALUATION
PROCESS CONTROL COMPONENTS (Cont'd)

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
PS/00 Blower Press Switch (Loss of Flow Alarm/Shutdown) Dwyer Model 1910-20	P = 15.696 T = 95°F Set Point 74" H2O	Standard industrial U/L pressure switches commonly used with burner packages for loss of air shutdown	None
CV 102A Reformer Process Air Check Valves NIBCO T-473-Y 1" Size	W = 88 lb/hr T = 95°F Pin = 15 psi Delta P = 4" H2O	Standard industrial check valve used on 40-kW field power plants	None
HCV 101, HCV 404 HCV 405, HCV 720, HCV 720A, HCV 720B, HCV 102, HCV 102A HCV 102B	Various power plant trim valves Jamesbury ball valve A-2236MT series line size as applicable	Used on PC-19, 4.8-MW power plant Standard industrial shutoff/trim valves	None
TSW 500 Coolant Exit Temp. Switch United Electric F11011-7BS	P = 10.5 psi T = 330°F Switch to trip for high temperature alarm	Standard industrial U/L listed temperature switch	None

POWER PLANT PROCESS COMPONENT EVALUATION

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
FE 500 Orifice Plate and Delta P Transmitter Daniels Orifice Plate (SST)-RT30 Rosemount Delta P Transmitter 1151DP4E22B1	W = 13,000 lb/hr Delta P = 100" H2O T = 330°F	Standard industrial instrument configuration for flow measurement Used on PC-19 and 4.8-MW power plant	None
PMP-500 Coolant Pump	Flow - 13,000 #/hr Delta P - 10.5 PSIG Temp - 330°F Fluid - Dowtherm-J	Standard commercial canned pumps are available Possible candidates 1) March Magnetic DR #TE75MD 2) Crane Canned Pump JA-1K-751	Verify canned design modifications for 350°F operation
BLO-100 Process Air Blower	Flow - 1113.9 #/hr Temp - 95°F Delta P - 28" H2O SCFM - 250.0 Inlet P. = 14.7 PSIA	Commercially available blowers are common in this size typical selections 1) Cincinnati - PB-18 - 28" Delta P 250 CFM - 3.66 HP \$1300 2) New York Blower - N19P-3 3 HP @ 220 CFM - 3500 RPM 3.45 HP @ 310 CFM	None

POWER PLANT PROCESS COMPONENT EVALUATION

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
BLO-302 Start Burner Recycle Blower	Flow - TBD Fluid - Burner Exhaust Temp - 400°-450°F Delta P - 3" H2O	Units available on a custom basis. Requires some engineering for 450°F Conditions 96 #/hr P 3" H2O, at 400 to 450°F Army PAP (ROTRON) operated at similar conditions	Shorter BRG life due to high T Higher cost
PMP-400 Feedwater Pump	Flow - 224 #/hr Fluid - H2O Temp - 107°F Delta P - 18.1 PSID P. = 14.7 PSI	Typically same application as 40 kW feedwater pump but with lower delta P requirement.	Pump life will be defined by wear associated with "clean" water
PMP -402 Circulating Pump Flow - 82.5 #/hr	Fluid - Hot H2O application to satisfy the Temp. - 175°F Delta P - 3 PSI Pin - 26.9 PSIA	This is of a metering pump requirements. low flow application. A standard ejector or venturi is an alternate approach.	Select pump satisfying low flow Cir
PMP-200 Fuel Pump	47.8 #/hr Fluid - #2 Fuel Oil Temp - 77°F Density - 37.4	A standard commercial burner pump Standard units run at 100 psig to produce acceptable nozzle spray into burner combustion zone.	None

POWER PLANT PROCESS COMPONENT EVALUATION

INVERTER SUBSYSTEM

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
INVERTER BRIDGE AND MAGNETICS	Rated 100 kWAC at 0.85 power factor continuous (118 kVA)	On-Site Program Verifies:	None - Inverter a direct derivative of the Gas Utility On-Site power plant program.
One Bridge per 100 kW System	Rated 120 kWAC at 0.7 power factor for 5 second overload	Basic high frequency, high current bridge technology, and microprocessor control logic	
Advanced gate controlled switching devices	Total harmonic distortion less than 5%, any single harmonic less than 3%	Design to meet the appliance electrical requirements in NEMA, ANSI and NEC specifications.	
High frequency pulse width modulation for regulation and harmonic control	Nominal output of 120/208 Vac, 3 phase, 4 wire	Design intended to be UL approved	
Dielectric to air cooling	Voltage regulation of $\pm 5\%$ from no load to overload	Commercial design practices to provide low cost package	
Fiber optics for control/protection communication lines	Transient recovery in less than 2 cycles	- Standard parts - Modular construction	
	Current limited for fault clearing	Design to meet EMI/RFI requirements	
		- IEEE STD 518-1977 - Telephone Influence factor (3000) - FCC79-555, 14686 - MIL-STD-461B - FCC regulations for industrial/commercial	

POWER PLANT PROCESS COMPONENT EVALUATION
INVERTER SUBSYSTEM

COMPONENT NAME	APPLICATION REQUIREMENTS	QUALIFICATION STATUS	DEFICIENCIES
ELECTRONIC CONTROLS AND UPS	Completely automated control and protection for a fuel cell power plant	On-site program verifies: Technology and advanced design	None - controller is a direct derivative of the Utility On-Site power plant program
Inverter and fuel cell process controls integrated into single electronic package	Four printed circuit cards (1) For inverter bridge (1) For inverter system functions (2) For fuel cell process controls	Design to utilize standard commercial components and practices to provide low cost and high reliability - Standard parts/commercially developed electronic circuit cards utilized where possible - Screened/burned-in electronic parts - Logic card manufacturer tested	
Use of advanced microprocessor technology			
Maximum use of off-the-shelf microprocessor circuit boards			
Fiber optic communications links		- Self checking/diagnostics designed in	
Software flexibility		- Design to minimize use of analog or "set-in-test" circuits, and maximize digital circuitry Design to meet EMI/RFI requirements - IEEE STD S18-1977 - Telephone Influence Factor (300) - FCC79-555, 14686 - MIL-STD-461B - FCC regulations for industrial commercial radiators	